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VOL.03

UNKNOWN WORLDS

EARTH | OCEAN | SPACE

Journey to the centre of the Earth

The weird anatomy of a black hole

Exploring Earth's most mysterious oceans

David Attenborough on his worst-ever expedition

Hunting for exoplanets

The daring mission to colonise Mars

Deep-sea monsters lurking in the abyss

Inside the world's most deadly volcano


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There's a starman waiting in the sky...

Behind the wheel of a Tesla Roadster, the mannequin 'Starman' is cruising around the cosmos, currently over a million miles from Earth.

This is surely one of the craziest things to have ever been sent into space. But, publicity stunt aside, the launch on 6th February did have a serious agenda – to test SpaceX's Falcon Heavy. The rocket was fired into low-Earth orbit with a whopping payload of 64 tonnes – the equivalent of hefting five double-decker buses into space.

The endeavour has all the elements of a great adventure – vision, risk-taking and bravery to challenge science as we know it and explore new frontiers. This whole special issue is about missions, voyages and expeditions that are pushing the final frontiers and exploring unknown worlds, from the depths of our oceans to the bowels of the planet to the remote reaches of deep space.

Starting with the underwater world, discover the divers using cutting-edge tech to plunge deep into the abyss (page 10), the bioprospectors hunting the oceans for new drugs to curb the rise of antibiotic-resistant superbugs (page 18), and the weird and wonderful deep-sea monsters lurking below the twilight zone (page 24).

On land, journey to the centre of the Earth (page 32), find out about the scientists searching for extremophiles miles under the surface (page 40), meet the people with the most extreme jobs in science (page 48), explore the world's most deadly volcanoes (page 52), and find out what remote spot David Attenborough got stranded on (page 58).

Finally, voyage around our Solar System and beyond. Find out about the current and future missions exploring the cosmos (page 63), our plans to colonise Mars (page 78), and the spacecraft hunting for exoplanets and black holes (page 89).

Plenty to keep both the keen explorer and armchair traveller happy. Enjoy!

Daniel Bennett, Editor

CONTENTS

OCEAN

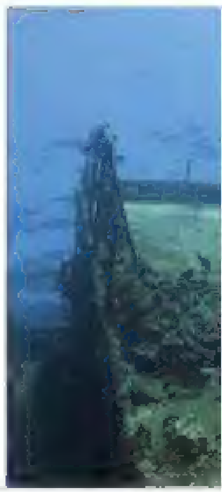
EARTH

SPACE

48
Find out about the most extreme jobs in science

10
Dive to the deepest depths of the oceans

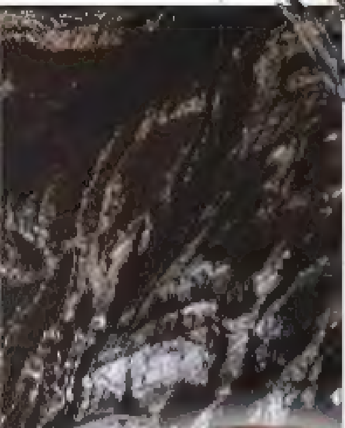
89
Explore exoplanets and black holes



70

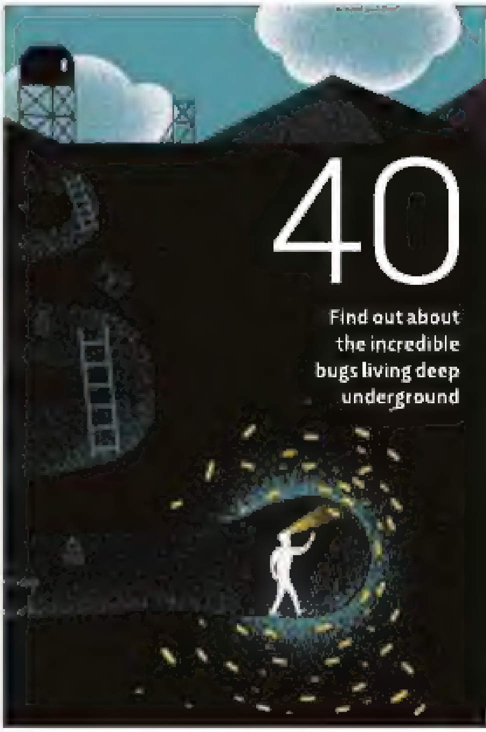
Find out about the mission into the Sun

24 Check out the weirdest deep-sea creatures



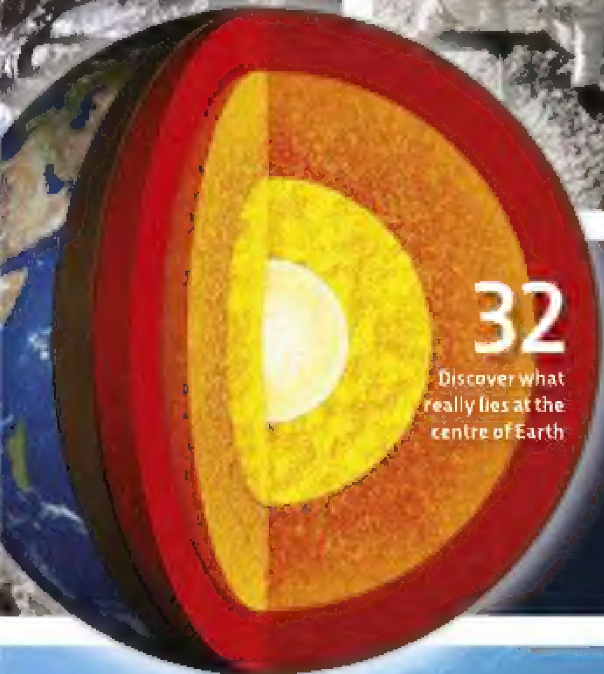
78

Discover how we'll colonise Mars



40

Find out about the incredible bugs living deep underground



32

Discover what really lies at the centre of Earth

Explore our Solar System 63

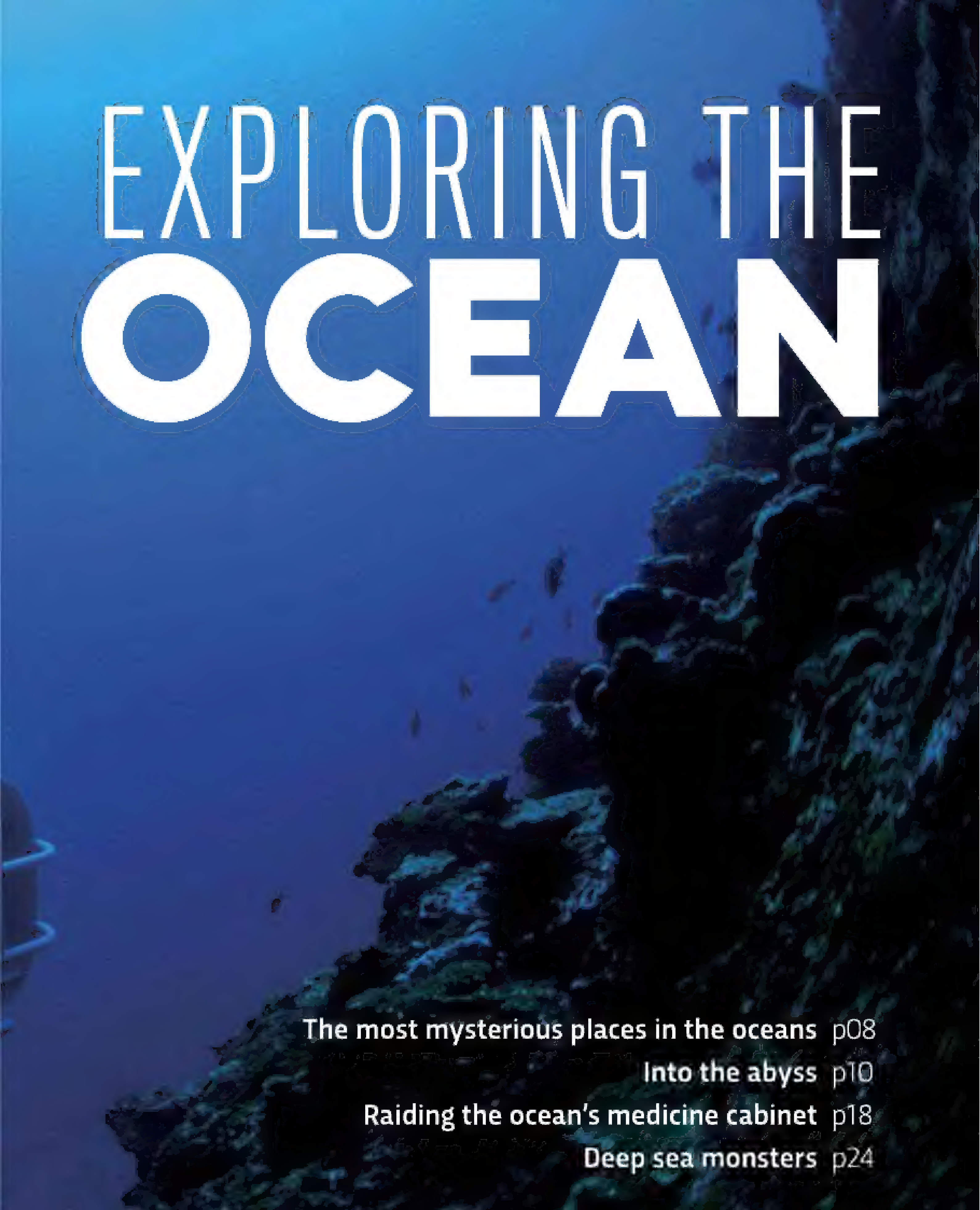
18

Meet the bioprospectors hunting for drugs to beat superbugs

52

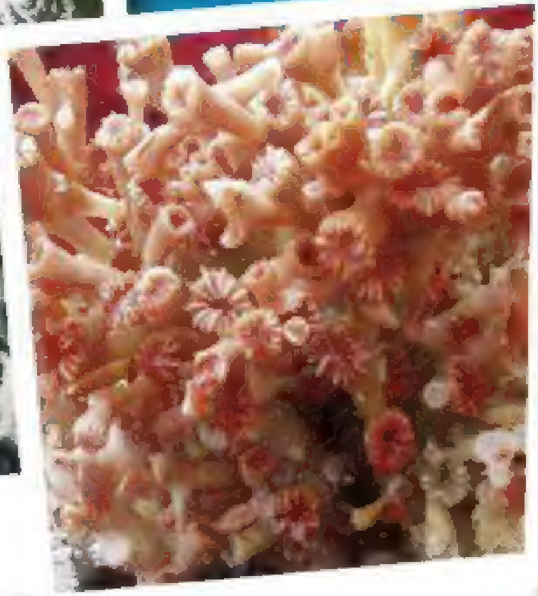
Find out about the world's most deadly volcanoes


GETTY

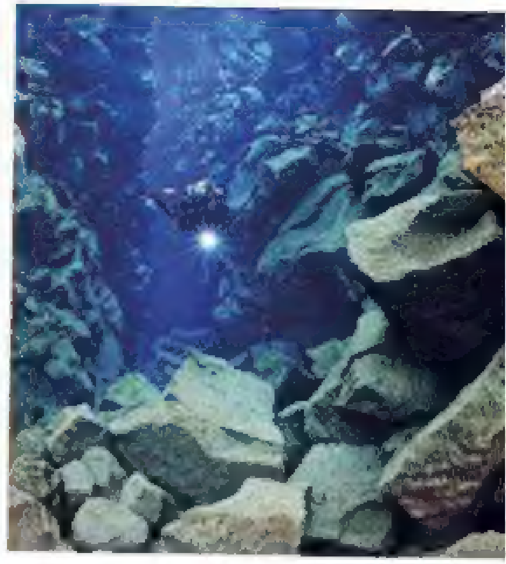


EXPLORING THE OCEAN

THE CASCADIA MARGIN



GREENLAND



SILFRA FISSURE

THE MOST MYSTERIOUS PLACES IN THE OCEANS

Little is known about these intriguing underwater worlds, whose dark depths and remote locations help guard their secrets

1 THE CASCADIA MARGIN

The Ocean Exploration Trust recently found 500 spots off the US west coast where methane bubbles out of the seabed like champagne, and where several little-known species thrive.

2 GREENLAND

In 2012, researchers stumbled across a coral reef while taking water samples 900m down off Greenland's southern coast. Little is known about it, but similar reefs in Norway are 8,000 years old.

YUCATÁN PENINSULA

THE ROSS ICE SHELF

THE CHAGOS ISLANDS

SILFRA FISSURE

In the middle of Iceland, this is the only place where you can swim in the crack between two continents (the Eurasian and North American plates). It gets 2cm wider every year.

YUCATÁN PENINSULA

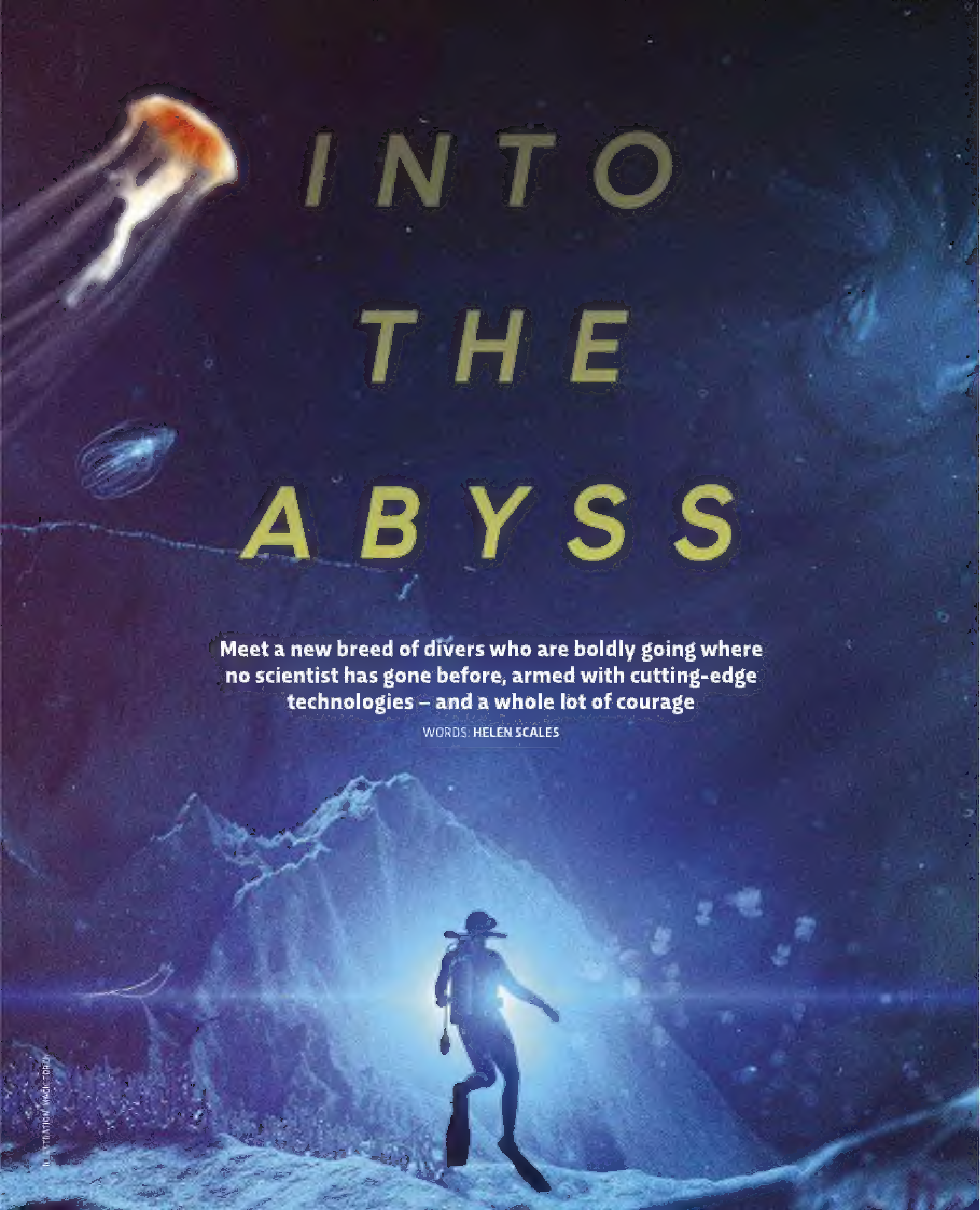
Thousands of deep sinkholes form part of the longest underwater cave system in the world. The caves are flooded with freshwater overlying saltwater and many remain unexplored.

THE ROSS ICE SHELF

Researchers drilling hundreds of metres through the world's largest ice shelf have found fish and crustacean species living underneath. How they got there – and survive – is a mystery.

THE CHAGOS ISLANDS

Few coral reefs have been studied deeper than 40m, but in the Indian Ocean, healthy deep reefs in the Chagos Islands could help shallower areas recover from 2016's mass coral bleaching.



INTO THE ABYSS

Meet a new breed of divers who are boldly going where no scientist has gone before, armed with cutting-edge technologies – and a whole lot of courage

WORDS: **HELEN SCALES**

Until about a century ago, it was thought that not much lived in the deep sea. With its average depth of around 3.5km, crushing pressures and permanent darkness, few people bothered looking there – what could possibly hope to survive in such a hostile environment?

According to the US National Oceanic and Atmospheric Administration (NOAA), 95 per cent of the oceans are still completely unexplored. But today's scientists have ditched the old ideas of a deep, empty ocean and flat, featureless seabed. They're keen to take a closer look beneath the waves and the latest generation of research equipment is opening up the depths like never before. New technology is helping scientists to understand the vital role the oceans play in the global climate and find bizarre creatures that offer clues about the origins of life on Earth.

DEEPER DIVING

Exploring the mysterious 'twilight zone'

"It feels like I'm somewhere I shouldn't be," says Jack Laverick, a PhD student at Oxford University, as he recalls being the first person to see part of a 100m-deep Caribbean reef. "This kind of exploration can give you tingles."

He's one of a new breed of scientists that are venturing deeper than most scuba divers ever go. Divers can now descend into the 'twilight zone', from 50m down, where sunlight begins to fade. Few have visited these depths, but now so-called rebreathers are making it possible.

Although invented before scuba equipment, rebreathers have only recently become safe enough for use in research. Instead of bubbling exhaled air into the water they recycle it, scrubbing out carbon dioxide and topping up the breathable oxygen.

Dominic Andradi-Brown, another deep-diving PhD student from Oxford, recounts the excitement of descending off an underwater cliff. "It feels like you're going off the edge of an abyss – anything could be below you."

Laverick and Andradi-Brown took part in Thinking Deep, a 2015 dive off the island of Utila in Honduras. They dove into the twilight zone to explore understudied parts of the oceans. Submersibles can go much deeper but regular scuba divers can't safely go beyond 40m. "There's this really understudied middle bit," explains Laverick.

"It feels like I'm somewhere I shouldn't be. This kind of exploration can give you tingles"

Corals are usually associated with the sunny conditions in shallow waters but less than a decade ago researchers confirmed that tropical coral reefs grow into the twilight zone. These 'mesophotic reefs' could provide species a refuge from the overfishing and rising sea temperatures found in shallower waters. Laverick is investigating whether shallow, damaged reefs could regrow from young corals born in the deep.

Andradi-Brown is studying fish. Below 60m, he's seen shark species that have been all but wiped out by fishing closer to the surface. "Coral reefs are a doom and gloom story at the moment," he says, "but these deep refuges are showing real potential."

CALL IN THE SEALS

How sensor-equipped seals are helping scientists peer below the Antarctic ice

Tagging elephant seals on an Antarctic beach isn't a job for the faint hearted. Mature males weigh up to four tonnes and can easily mistake a human for another seal looking for a fight. "Elephant seals don't have good vision," says Dr Horst Bornemann, a researcher from Germany's Alfred Wegener Institute for Polar and Marine Research. "You want a team who can anticipate their behaviour and fend off territorial males."

There's a good reason for working with such colossal, bad-tempered animals in remote, sub-zero conditions though. Southern elephant seals, the deepest diving seal species, can dive below 2,000m for hours at a time, so fixing small, electronic sensors to their heads can transform them into a fleet of researchers. These sensors gather data on the seals' movements – how deep they dive, what they eat and where they go – and can ping the information back when the seal surfaces for air.

Tagged seals can help answer important questions about the oceans. Over seven years, close to 20,000 dives were logged by dozens of elephant and crabeater seals in parts of the Bellingshausen Sea, off the Antarctic Peninsula. Another recent study used information from a programme called MEOP (Marine Mammals Exploring the Oceans Pole-to-Pole) to understand more about why West Antarctic ice shelves are melting, showing that a layer of warm, salty water is edging up to the continental shelves surrounding Antarctica.

"There are ice-covered areas in which it's a huge effort to manoeuvre a ship," says Bornemann. "But seals can cope with any icy conditions, all year round. So you get perfect winter data."

Attaching sensors to four-tonne elephant seals can be dangerous

ROBOT SUBS

How gliders are going where humans can't

"Very small, gentle submarines." That's how oceanographer Dr Pierre Testor from Paris's Pierre and Marie Curie University describes the underwater robots he works with. In the 1980s, scientists came up with the idea of long-range vehicles that could explore hard-to-reach areas of the oceans. Today, fleets of autonomous robots, known as gliders, scour the seas for months at a time, gathering crucial data about how the oceans work.

When Testor began his glider studies a decade ago, the worry of not knowing if costly equipment would make it back in one piece was tempered by the excitement of new discoveries. "I felt I was starting to do oceanography in a different way," he recalls. Since then he's seen gliders used in all spheres of ocean science, from physics to biology.

Current gliders can reach depths of 1,000m, but Testor is part of BRIDGES, a European project that's developing new gliders that go much deeper. "We plan to produce a glider that's able to go to around 6,000m," he says. This means they'll be able to reach around 98 per cent of the oceans. A big part of the gliders' success is their efficiency: they consume about the same amount of power as two Christmas tree lights.

The new BRIDGES gliders are intended for academic and industrial uses, including monitoring pollution from deep-sea mines. Rare-earth minerals are in huge demand from the electronics industry and could soon be extracted from the seabed.

Conservationists are concerned that such mines will be difficult to monitor. It's hoped gliders will keep an eye on operations deep beneath the waves. Equipped with acoustic sensors, they'll be able to detect clouds of metal-rich sediments churned up by the mines.

BELOW: A depth chart of part of the Gulf of Lion in the Mediterranean, produced using one of the BRIDGES gliders.

LITTLE MERMAID

Building a distinctly human-like underwater avatar

Measuring 1.5m in length and weighing 180kg, OceanOne is quite unusual for a remotely operated underwater vehicle. Described as a 'robo mermaid', it has a head, two cameras for 'eyes' and a pair of fully articulated arms, complete with wrists and fingers. OceanOne acts as an underwater avatar, allowing its controllers on the surface to feel as though they're diving down to inaccessible depths while remaining safe and dry. Not only can its human pilot see what the robot sees via the stereoscopic cameras in its head, they can feel what it's holding thanks to haptic feedback that's transmitted from sensors in the robot's hands.

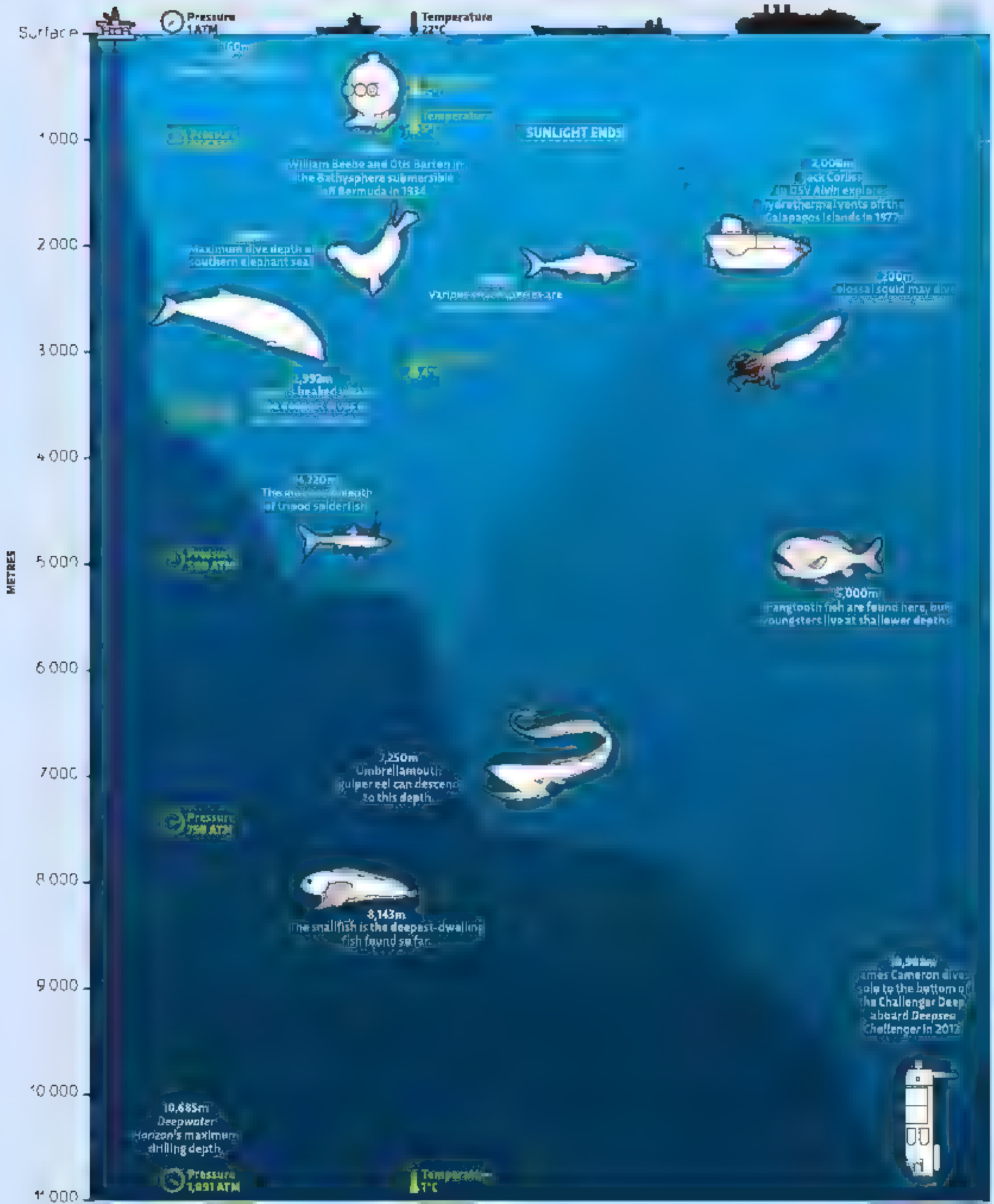
To a certain extent, OceanOne can even think for itself. On board processors analyse camera footage and adjust the thrusters in the robot's tail to make sure it doesn't bump into anything. If sensors detect an unavoidable upcoming collision, the robot braces its arms to cushion the impact.

Built by a team at Stanford University, OceanOne's first mission, in April 2016, was to explore a 17th-Century shipwreck, *La Lune*, lying 100m below the surface of the Mediterranean. The robot carefully swam around the wreck and successfully retrieved ancient artefacts without damaging them.

The idea is that eventually the robo mermaid will be able to perform other skilled tasks, such as examining fragile coral reefs or operating machinery in places such as deep-sea mines and oil rigs.

BRIDGEL X2 FREDERIC OSADA/TEDDY SEGUIN/DRASSM

WHAT LIES BENEATH



GOING DOWN DOWN DOWN DOWN

How next-generation submersibles are enabling scientists to dive deeper than ever before

"It's as close to being in space as you can be on the Earth," says Oxford University's Prof Alex Rogers, as he recalls his journey to a depth of 3,380m inside the Japanese submersible *Shinkai 6500*. "You are so remote from your normal environment. There's a real sense of isolation."

Rogers is science director of a new deep ocean research initiative called Nekton. On the first Nekton expedition in 2016, he explored the deep sea around Bermuda inside a Triton submersible. This two-person, three-tonne sub is relatively small and lightweight compared to many other submersibles, and highly manoeuvrable. It also has a huge acrylic dome, giving scientists fantastic views of the ocean for observation and research. "The submersibles are absolutely fantastic. It's very James Bond," says Rogers.

Among the things that Rogers and the Nekton team observed were huge forests of tree-like black corals stretching down to Triton's depth limit of 300m. Giant sea fans and enormous sponges add to the strange living seascape. To go deeper, the team will send down remotely operated vehicles and other deep water probes.

The long-term aim for Nekton is to document the life at depths between 200m and 3,000m in 14 regions worldwide. These regions are defined by particular attributes, including temperature, salinity and currents. The team will also measure the health of these deep ecosystems and look for signs of human impacts, such as trawling and plastic waste. Who knows what else could be lurking there?

Being in the Triton subs gave Rogers a new perspective on the ocean's scale. "You look across and see the other sub in the distance as this tiny toy," he says. "There are many scenes that lodged in my memory: majestic cliffs and landscapes that can make you feel quite small."

Dr Helen Scales (@helenscales) is a marine biologist, writer and broadcaster. Her next book, *Eye Of The Shoal*, is out in May.

BBC Radio 4

Listen to an episode of *The Infinite Monkey Cage on Oceans: What Remains to Be Discovered?* bbc.in/2npCkrz

TRITON & NEKTON, NEKTON & XL CATLIN DEEP OCEANS SURVEY, ILLUSTRATION: CHRIS PHILPOT

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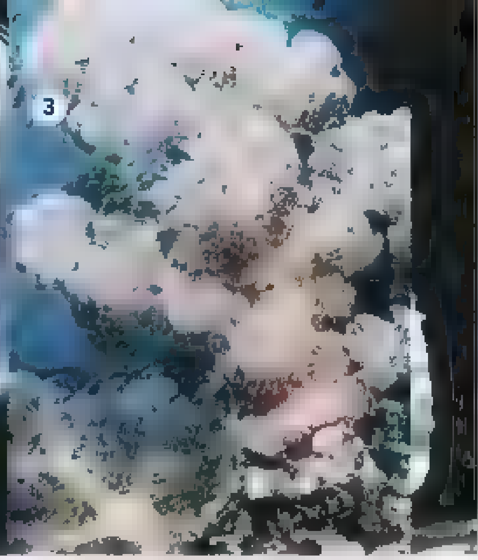
2

3



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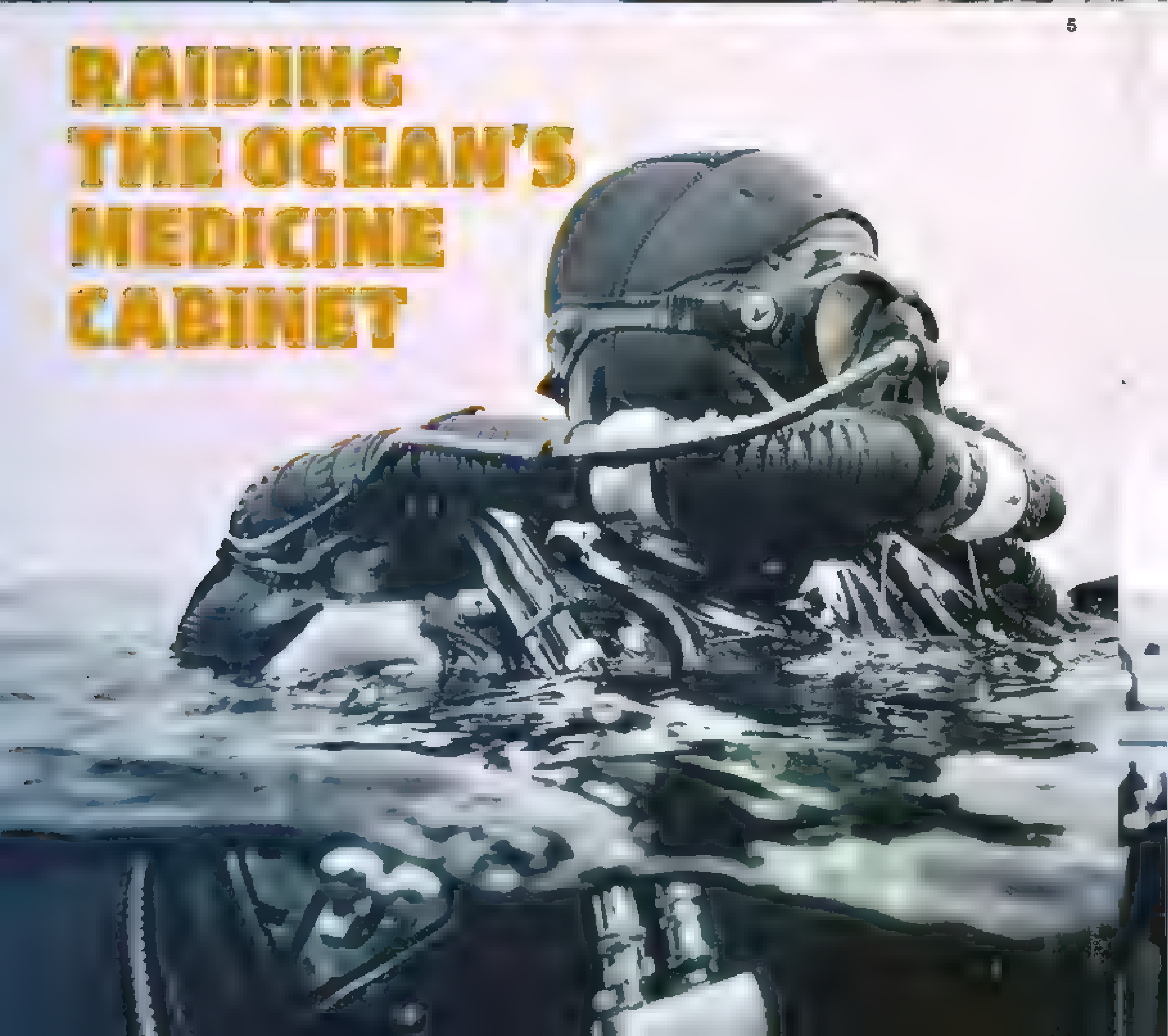
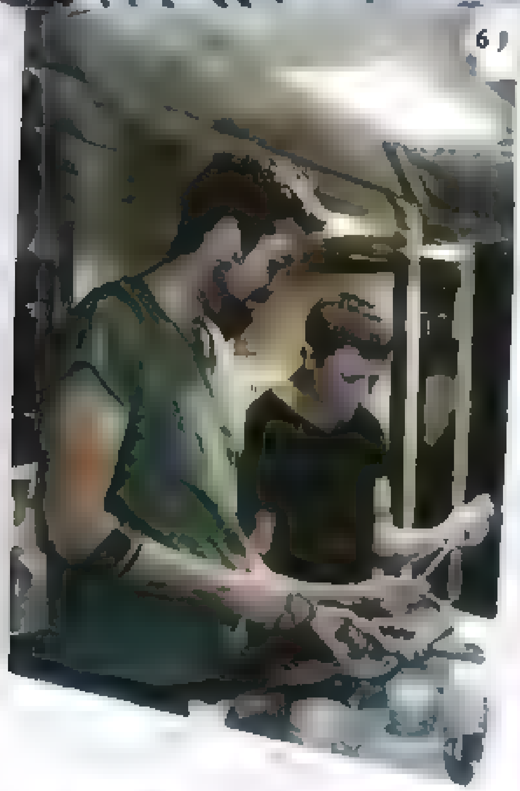
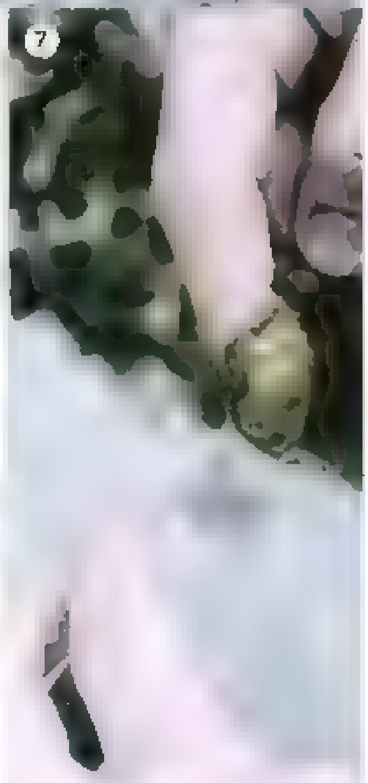
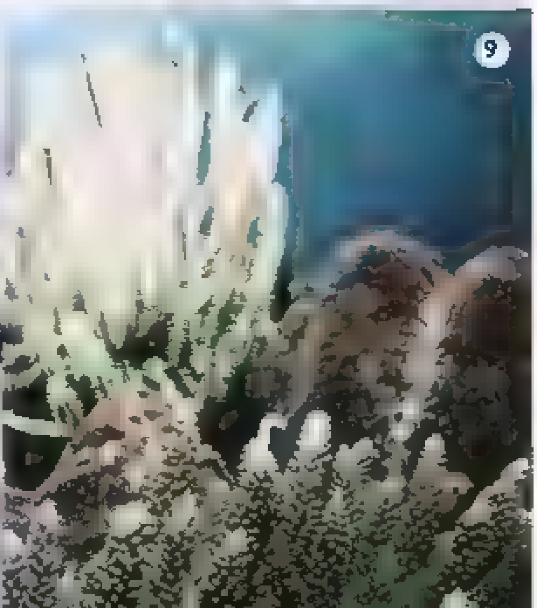
RAIDING THE OCEAN'S MEDICINE CABINET









Antibiotics are losing their effectiveness against disease. But the world's waters could be full of new drugs, just waiting to be discovered

WORDS: **HELEN SCALES**

Mud and sponges probably don't feature highly on most scuba divers' bucket lists. But scientist and explorer Brian Murphy, based at the University of Illinois at Chicago, has his sights set on the sediments lurking at the bottom of lakes and the gooey animals clinging to submerged shipwrecks. And for good reason. He recently brought back a blob of mud from Lake Michigan and found it contained bacteria that make two previously unknown molecules. Lab tests showed that this class of compounds is lethal to the bacterium that causes tuberculosis, a disease that existing drugs are struggling with. "For millions of years bacteria have fought one another," says Murphy. "We're just harnessing that power."

Around the world, superbugs are on the rise. Back in 2016, two patients in the US were discovered with strains of *E. coli* that were resistant to many antibiotics, including drugs only normally prescribed as a last resort. It's an alarming trend – bacteria are gaining the upper hand in their battle against the antibiotics we use to kill them, and their advantage is increasing thanks to our overuse of these drugs.

"The way to combat drug resistance is to find new chemistry," says Murphy. He's

one of many modern day prospectors who are searching for that new chemistry underwater.

PLUMBING THE DEPTHS

From icy polar seas to scorching hydrothermal vents, and from coral reefs to inland lakes, the vast, aquatic realms covering seven tenths of our planet are home to an immense diversity of life. They include many animals that evolved complex chemical defences, along with a profusion of microbes: it's thought that around 90 per cent of oceanic life is microscopic. From among these creatures, researchers are uncovering molecules that could form the basis for new medicines.

Tapping the natural world for pharmaceuticals is nothing new – pop an aspirin and your headache will be soothed by a substance that was discovered in willow tree bark. With the

The hope is that nature has plenty more in its medicine cabinet for us to dip into

rising tide of drug resistance, the hope is that nature has plenty more in its medicine cabinet for us to dip into. The trick is sifting through all those potent chemicals to find the ones that could fight disease.

"It's no secret that there's an incredibly high failure rate when it comes to developing drugs," says Murphy. "It's really difficult to find a set of molecules that are not only capable of targeting a specific disease and but can also do it within the incredibly complex environment of the human body."

To help with this, Murphy is working to smarten up the sample collection process, as it's one of the few steps in drug development that hasn't seen a major revolution in recent decades. According to Murphy, looking for molecules in original places is an important

PREVIOUS PAGE

1 Diving the Great Lakes

2 Testing antibiotics in the lab

3 Animals on coral reefs have evolved interesting chemical defences

4 One of Brian Murphy's students leaps into the water to hunt for new drugs

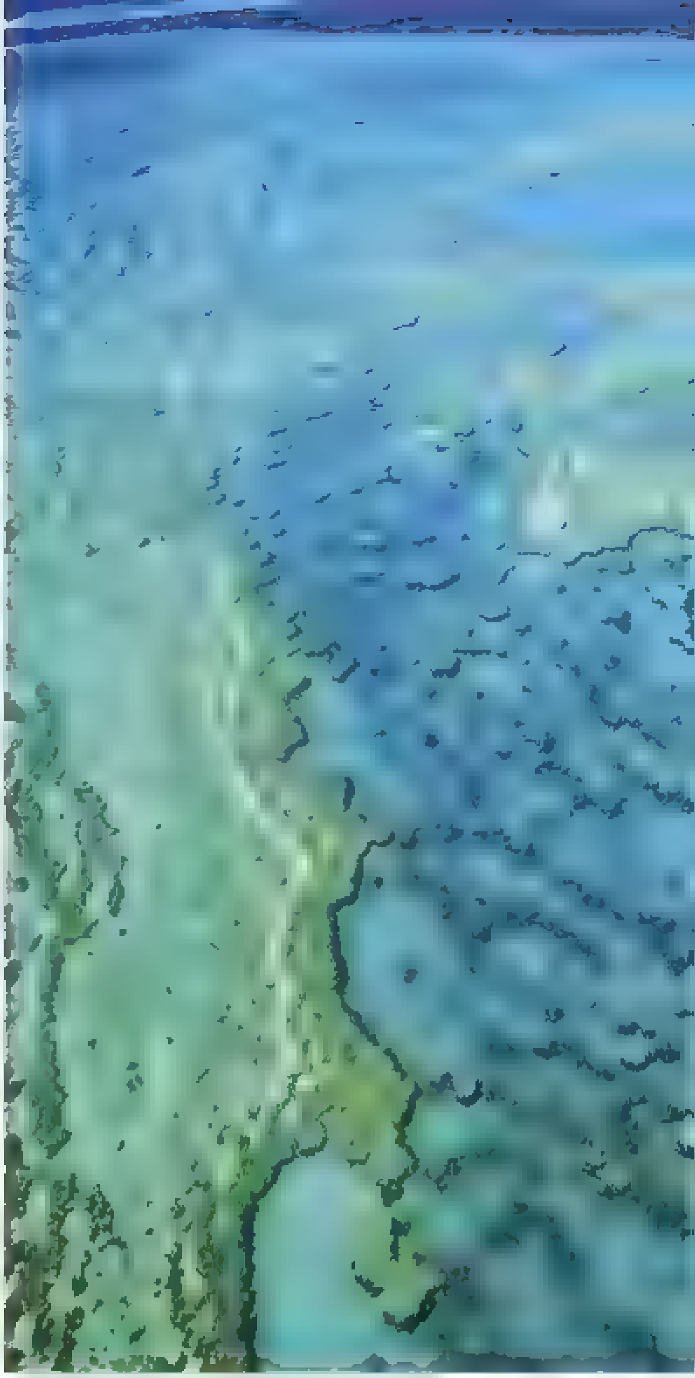
5 The Great Lakes in the US are a popular dive spot as they contain hundreds of well-preserved shipwrecks

6 Michael Mullowney (left) and Brian Murphy processing deep-sea sediments

7 Gathering Icelandic algae for research

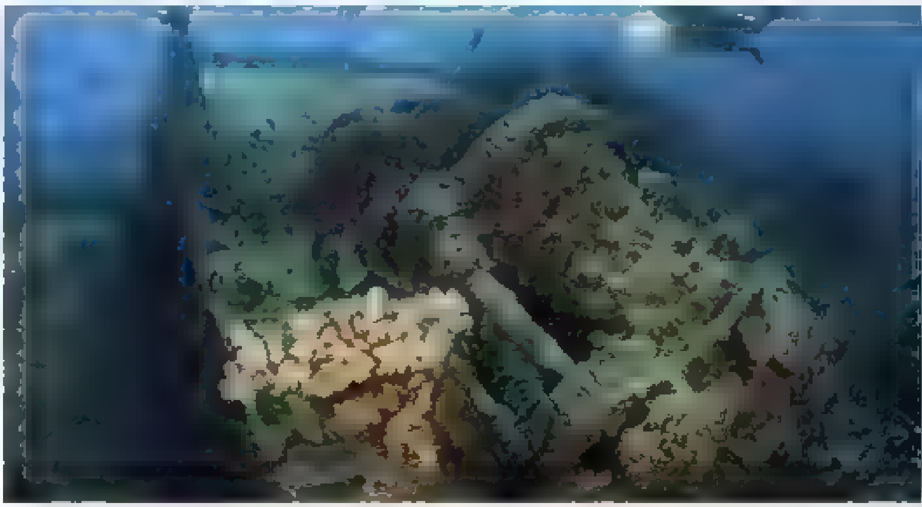
8 Brian Murphy with bacteria he's collected – some of these colonies contain a specific group of bacteria that's widely used in antibiotics

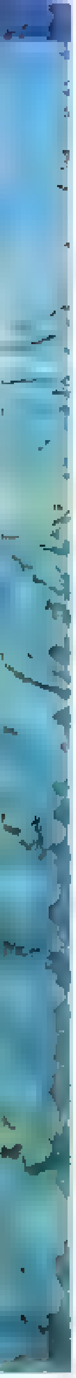
9 Bioprospectors first looked to coral reefs in the 1950s



RIGHT **The Great Barrier Reef spans 344,400km² – that's a lot of area to search for potential drugs**

BELOW Shipwrecks act as artificial reefs and become colonised with many species





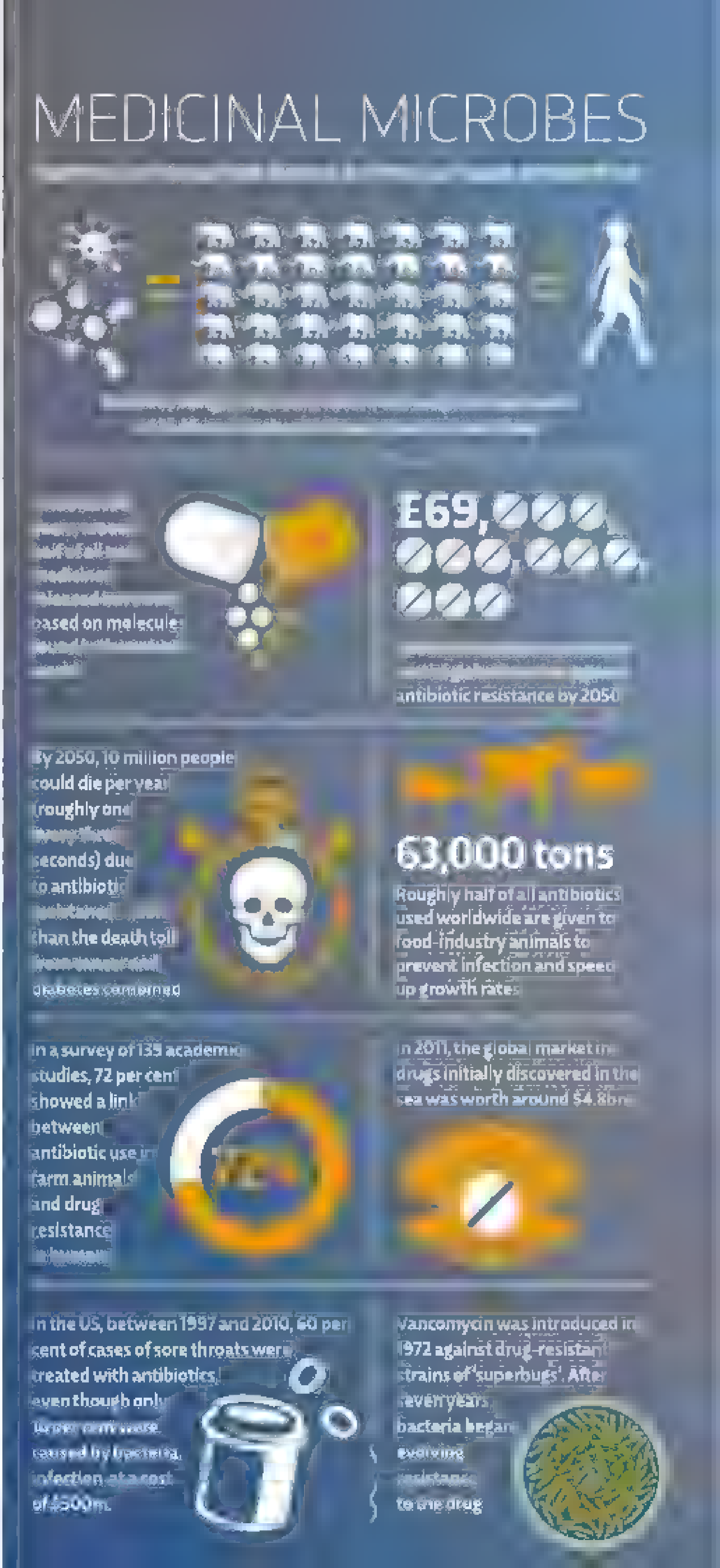
part of drug development, so he decided to use a new resource altogether: the general public.

Chatting with recreational scuba divers gave Murphy the idea of searching shipwrecks for sponges. These unprepossessing animals spend most of their lives stuck in place, sifting the water for food and taking on hordes of bacteria. "Bacteria can constitute up to 30 or 40 per cent of sponge biomass," Murphy explains. Freshwater sponges are a common sight across the USA's Great Lakes but almost nothing is known about them. Rather than go out himself and gather sponges – a time consuming and expensive business – Murphy rolled out a citizen science project asking divers to collect tiny samples for him while they're out. Ultimately, Murphy wants to map the distribution of sponges and bacteria across the lakes so that future efforts can be more effective and will zero in on fruitful spots, both in the Great Lakes and beyond.

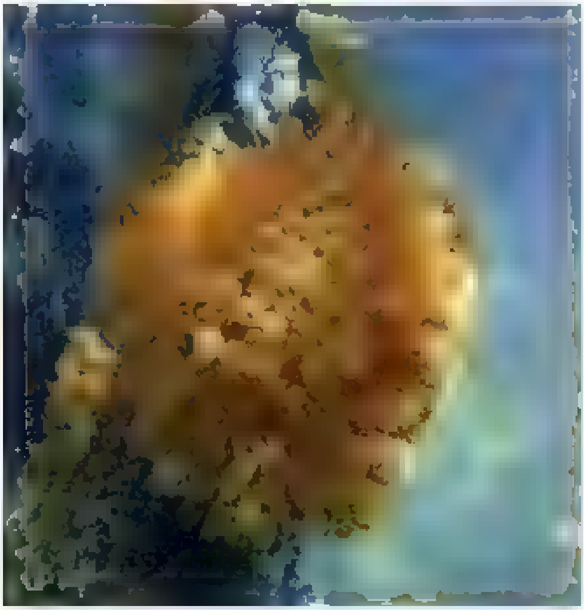
DIVERSE OCEANS

When bioprospectors first turned to the oceans in the 1950s, their initial targets were coral reefs. These bustling ecosystems, packed with species, are a logical place to look and they've yielded many natural products, including some that made it to the end of the drug development pipeline. One early discovery was chemotherapy agent cytarabine, approved in the US in 1969 and originally found in a sponge on a Florida Keys reef. Another cancer-fighting agent called trabectedin, which came from a Caribbean sea squirt, has been used in Europe since 2007 and in the US since 2015.

Elsewhere, other researchers are hunting for novel chemistry even further beneath the waves. An international team called PharmaSea, led by Prof Marcel Jaspars, is searching for new antibiotics in the deep sea, including at the bottom of trenches – the deepest parts of the oceans. Jaspars describes these as 'negative islands' sticking down into the seabed, instead of pointing up. "It's possible there have been millions of years of separate evolution in each trench," he says. Jaspars and his collaborators send unmanned probes miles down into the depths to bring back mud loaded with unique bacteria. Techniques for keeping these extreme creatures alive in the lab have advanced in ●



Brian Murphy's researchers hunt for new antibiotics in unusual locations, such as this waterfall in Iceland



ABOVE PharmaSea researchers scouring through oceanic mud

LEFT Some sea squirts contain cancer-fighting agents

"It's possible there have been millions of years of separate evolution in each trench"

recent years, so experiments can be carried out. According to Jaspars, they've done around 100,000 tests, with targets including the so-called ESKAPE pathogens. This group of six bacterial strains are showing growing resistance to multiple existing antibiotics.

Ultimately, the PharmaSea team aims to narrow down two compounds that can be produced at a larger scale and put forward for pre-clinical trials. So far, their most promising finds are compounds that could be effective against diseases of the nervous system, in particular epilepsy and Alzheimer's disease.

BENEFITS FOR ALL?

But who owns these discoveries from the deep? The word 'bioprospecting' usually has a negative connotation. At worst, it brings to mind indigenous people giving away their knowledge of traditional medicines and receiving little

BRIAN MURPHY, PHARMASEA, LEEN NASH

reimbursement. Thankfully, things have moved on and protocols for sharing benefits are now commonplace. Prior to collecting anything, researchers will generally enter written agreements with the country of origin. In 2010, the international Nagoya Protocol came into effect, making such agreements a legal requirement. But not everyone is signed up to Nagoya – the US is notably absent.

The high seas begin 200 nautical miles from shore and don't technically belong to anyone, making them difficult to police. Currently, the UN Convention on the Law of the Sea (UNCLOS) covers certain activities including deep-sea mining and laying cables, but it says nothing about biodiversity. Formal discussions got underway in 2015 to amend UNCLOS to encompass bioprospecting, but it's likely to be several years until it becomes regulated.

Various views are on the negotiating table. "The G77 and China believe that it should be the Common Heritage of Mankind, which would mean everybody could benefit," explains Jaspars. The idea is that one single nation or company shouldn't be allowed to solely benefit.

On the other hand is the concept of Freedom of the High Seas, backed by the US and Norway, which would give any nations freedom to bioprospect in the high seas, just as anyone can fish there. They could research anywhere and hold on to the profits. Other groups, including the EU, are keen to find a solution.

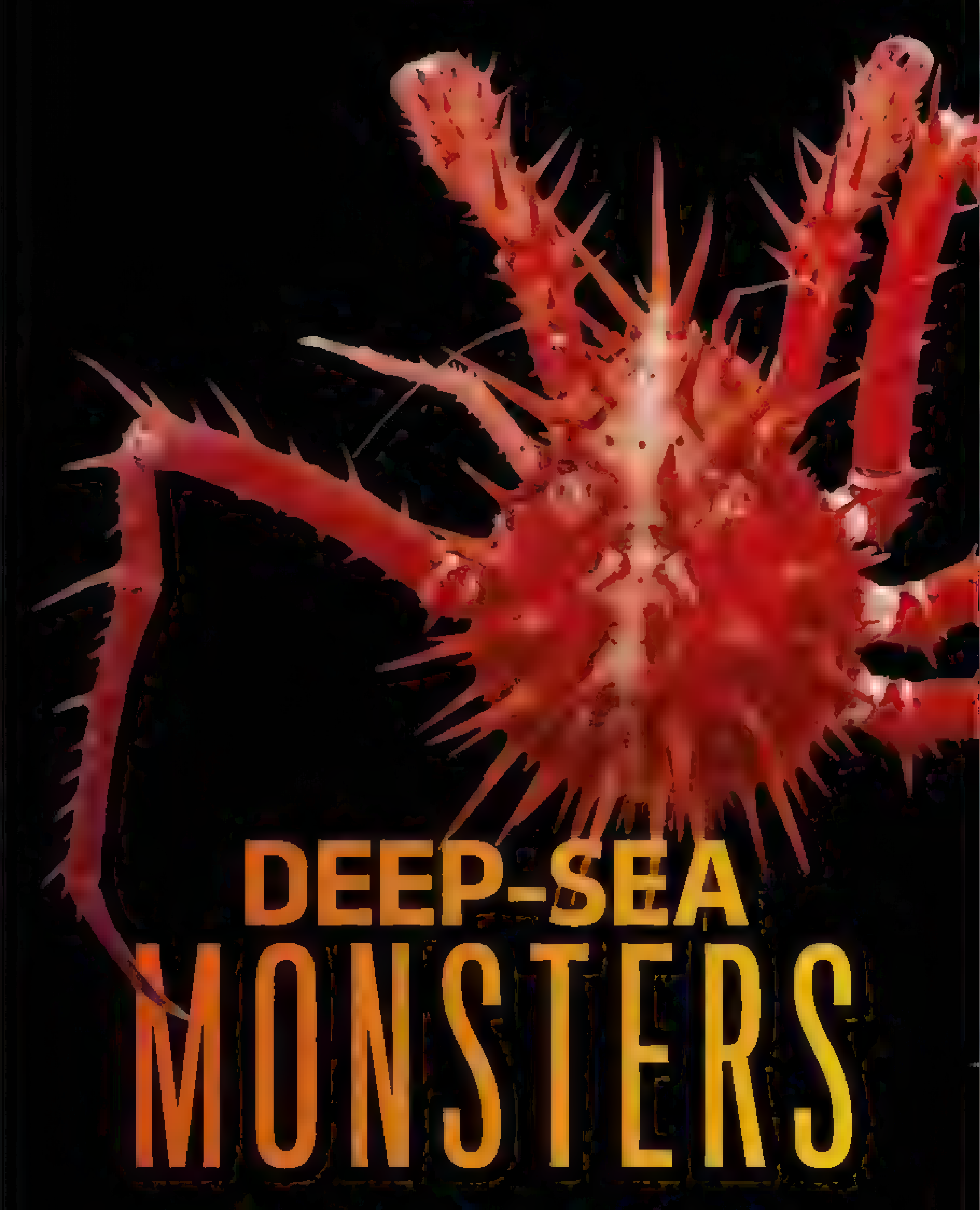
NEW WAYS AHEAD

Back in the lab, Murphy and his team have built up a collection of over 1,500 aquatic bacteria and are using them to create libraries of small molecules to screen against bacteria, pathogens and cancers.

But the race is on and bioprospectors will have to hurry. Reefs around the world are ailing, and human activities continue to threaten the health and biodiversity of Earth's oceans, rivers and lakes. Let's hope we can find the drugs and cures we need before our planet's waters become irrevocably sickened.

Dr Helen Scales (@helenscales) is a marine biologist, writer and broadcaster. Her next book, *Eye Of The Shoal*, is out in May 2018.

Watch clips from the landmark BBC One series *Blue Planet II* bbc.in/2FvKwgf


DEEP-SEA
MONSTERS

SPINY CRAB

With its spectacularly spiky body armour, this crab is immensely well protected as it stalks the seabed. Even its colour is protective, helping it hide in the dark depths because seawater absorbs red light. "You lose [red light] pretty quickly as you go down, so everything becomes blue," says Dianne Bray who was part of the expedition that found this specimen. This means that red pigments appear black, which would make the crab incredibly difficult to spot. Most deep-sea animals haven't evolved red vision – an added bonus for this crustacean.

For the first time, scientists have explored the deep sea off Australia, revealing a whole new world that's filled with bizarre creatures

WORDS: **HELEN SCALES**
PHOTOS: **ROB ZUGARO/ASHER FLATT/CSIRO**

Faceless fish, zombie worms and herds of sea pigs were among the wonders hauled up from the ocean depths by a research team working off Australia's east coast last year. Scientists from seven countries spent a month on the research vessel RV *Investigator*, starting in Tasmania and working their way north as far as the Coral Sea. While the shallower waters in this region are well known, this was the first expedition to focus on the unexplored depths.

Along the way, the team, led by Dr Tim O'Hara from Museums Victoria, mapped the seabed in detail for the first time with underwater cameras and sonar. They discovered rock-covered plains, colossal canyons and mountains. At every 1.5° of latitude they dropped a trawl net to the seabed. It took up to six hours for the net to go down to 4,000m (2.5 miles) and come back up. "It makes you appreciate what you get," says Dianne Bray, a fish specialist from Museums Victoria who was aboard the ship. "These things are so valuable and precious."

A metal sledge was also dragged along the bottom to gather mud-dwelling creatures and sample the seabed for signs of pollution. As well as cans and bottles, the sledge brought up piles of clinker – residue from coal-powered steamships that used to ply these waters in the 1800s and early 1900s.

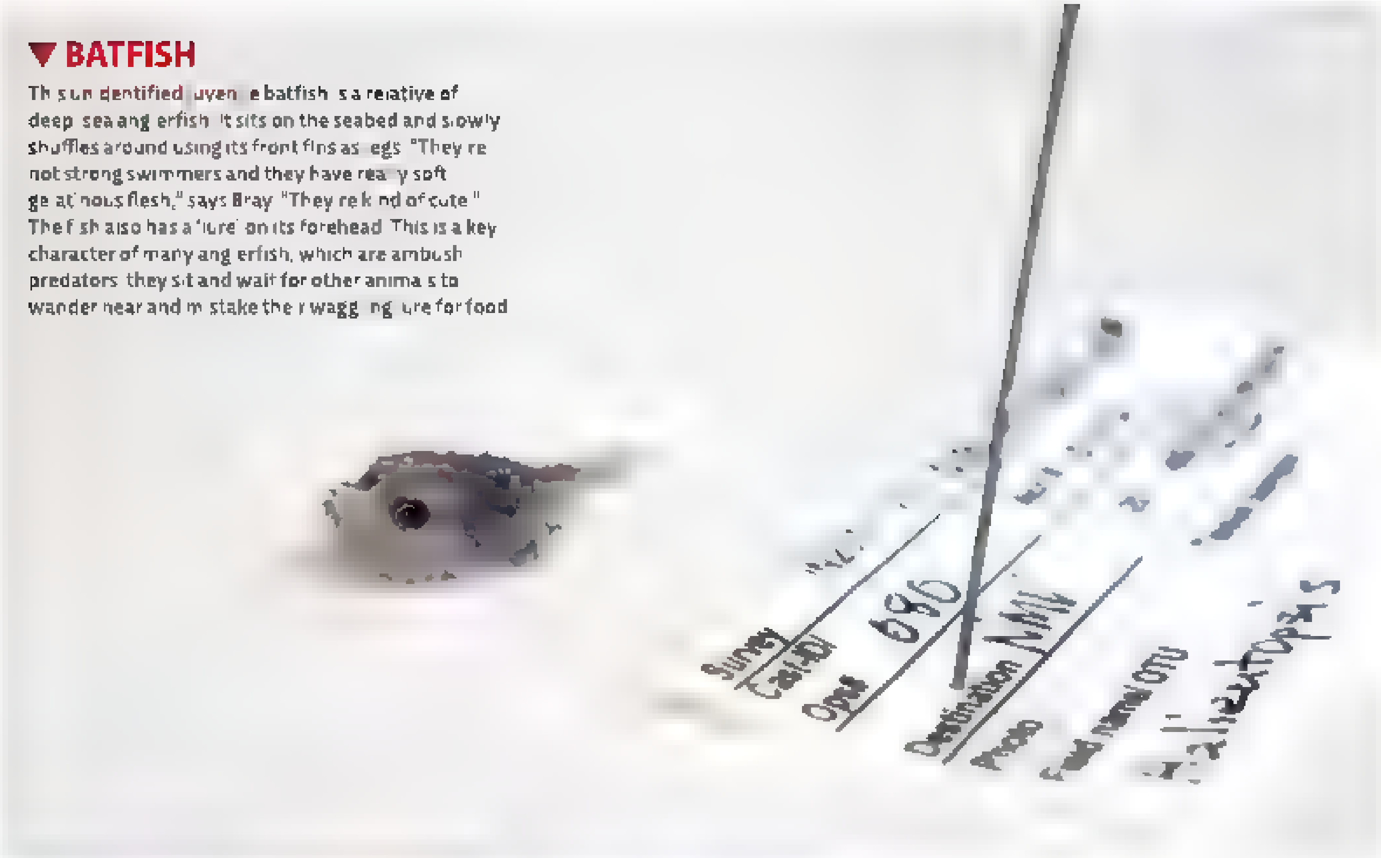
Of the thousands of animals that were collected, perhaps a third are new to science, although it'll take months of work to tease out the details. The preserved specimens will be used for generations, to understand how Earth's biodiversity is changing. "They're for the people who aren't yet born, who will ask questions that we can't even envisage [and answer them] using methods that we can't imagine," says Bray.

▲ LIZARDFISH

Two menacing lizardfish were collected on the trip, from a depth of 2,500m (1.6 miles). "It has nasty teeth," says Bray. Huge eyes help them detect the faint glow of bioluminescence, a form of light generated by many marine animals. Lizardfish are hermaphrodites, which means they have both female and male sex organs. This is a great reproductive strategy in the vastness of the deep sea, as the fish don't have to worry about finding a partner of the opposite sex when they want to reproduce – any member of the same species will do.

◀ GELATINOUS CUSK EEL

This fish lives in the permanent dark and has tiny eyes that may not work well. Yet somehow, it finds mates in the inky depths and gives birth to live young. The research team found another cusk eel species, which they nicknamed the 'faceless fish'. But it turned out not to be new to science – it had been collected 140 years ago in the northern part of the Coral Sea, by the British ship HMS *Challenger* during the first round-the-world oceanographic expedition. The new specimen is already on display at Museums Victoria.



▼ BATFISH

This unidentified juvenile batfish is a relative of deep-sea anglerfish. It sits on the seabed and slowly shuffles around using its front fins as legs. "They're not strong swimmers and they have really soft gelatinous flesh," says Bray. "They're kind of cute." The fish also has a 'lure' on its forehead. This is a key character of many anglerfish, which are ambush predators: they sit and wait for other animals to wander near and mistake their waggling lure for food.

◀ COOKIECUTTER SHARK

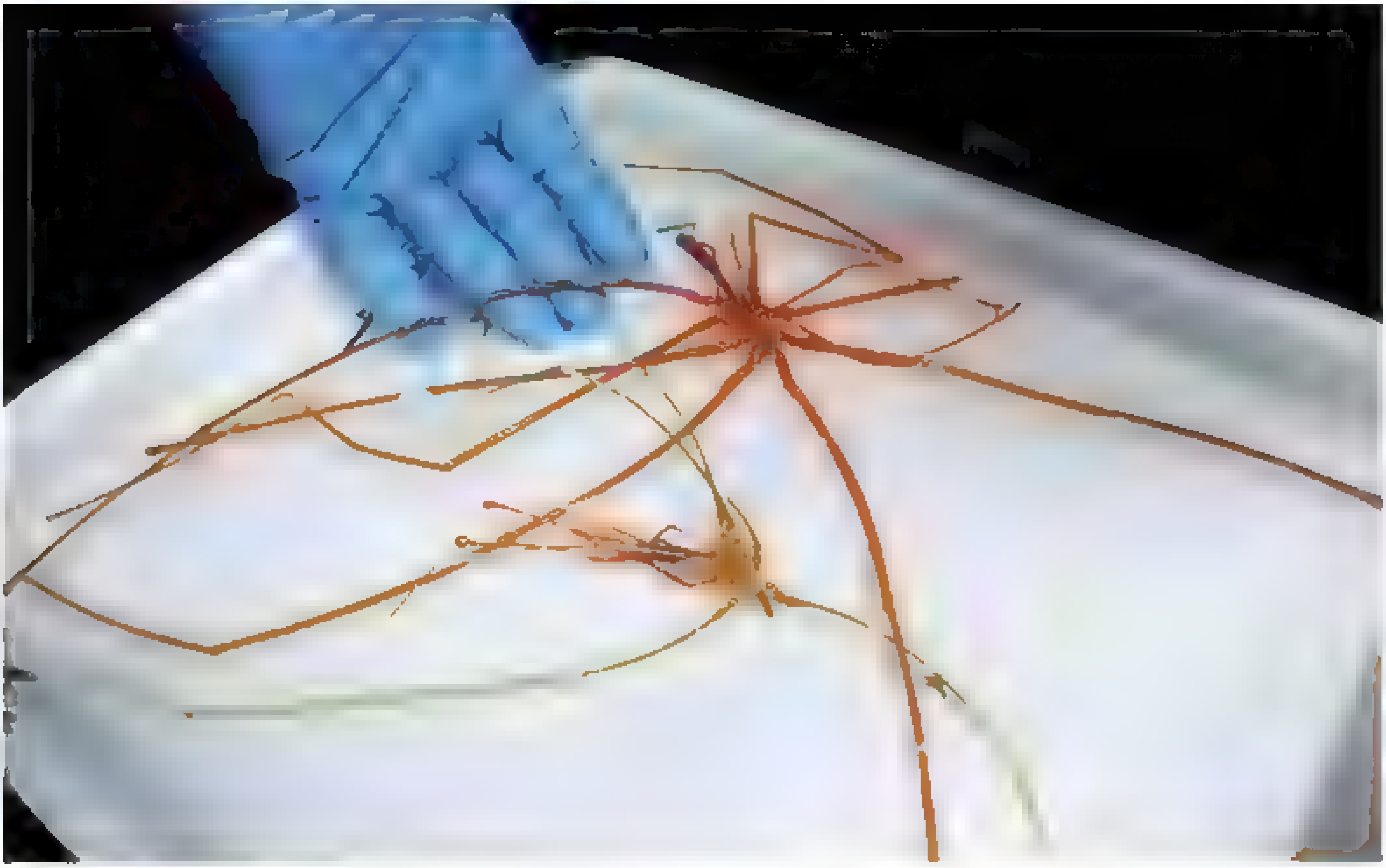
These fearsome sharks are rarely seen alive, but are mostly known from the circular wounds they leave in their prey (hence their name). They spend their days in the 'twilight zone' 1,000m below the surface, then rise up at night to hunt in shallower waters. The sharks measure about half a metre in length and latch onto large fish, dolphins and whales, before slicing out a plug of flesh with their razor-sharp teeth. Cookiecutters glow in the dark, which eliminates their shadow in the dim blue light of the twilight zone. A dark band on their skin may fool their victims into thinking they're smaller prey fish, which lures them within striking distance.

CORALLIMORPH

These invertebrates belong to the same group as anemones and corals. They have tentacles and stinging cells, called nematocysts, for snagging small prey. Unlike more familiar reef-building corals, corallimorphs don't secrete a calcium carbonate skeleton and they don't form colonies. Countless other spineless creatures were brought up in the expedition's sampling nets and preserved specimens will be sent around the globe for experts to identify. But it's still too soon to say how many species are new to science. "In terms of invertebrates, that's a fair way down the track," explains Bray.

PEANUT WORM

Let's face it – we're all thinking the same thing. But this is not a penis worm (although they do exist: a whole phylum of penis worms lives in mud in shallower seas). This worm belongs to a different group of seabed dwellers, called 'sipuncula'. They can retract the front part of their bodies when they're threatened, making them look more like peanuts. There are male and female peanut worms, which can either reproduce sexually, by releasing sperm and eggs, or asexually, by splitting themselves in half to produce identical clones – handy if they can't find a mate.



▲ SEA SPIDER

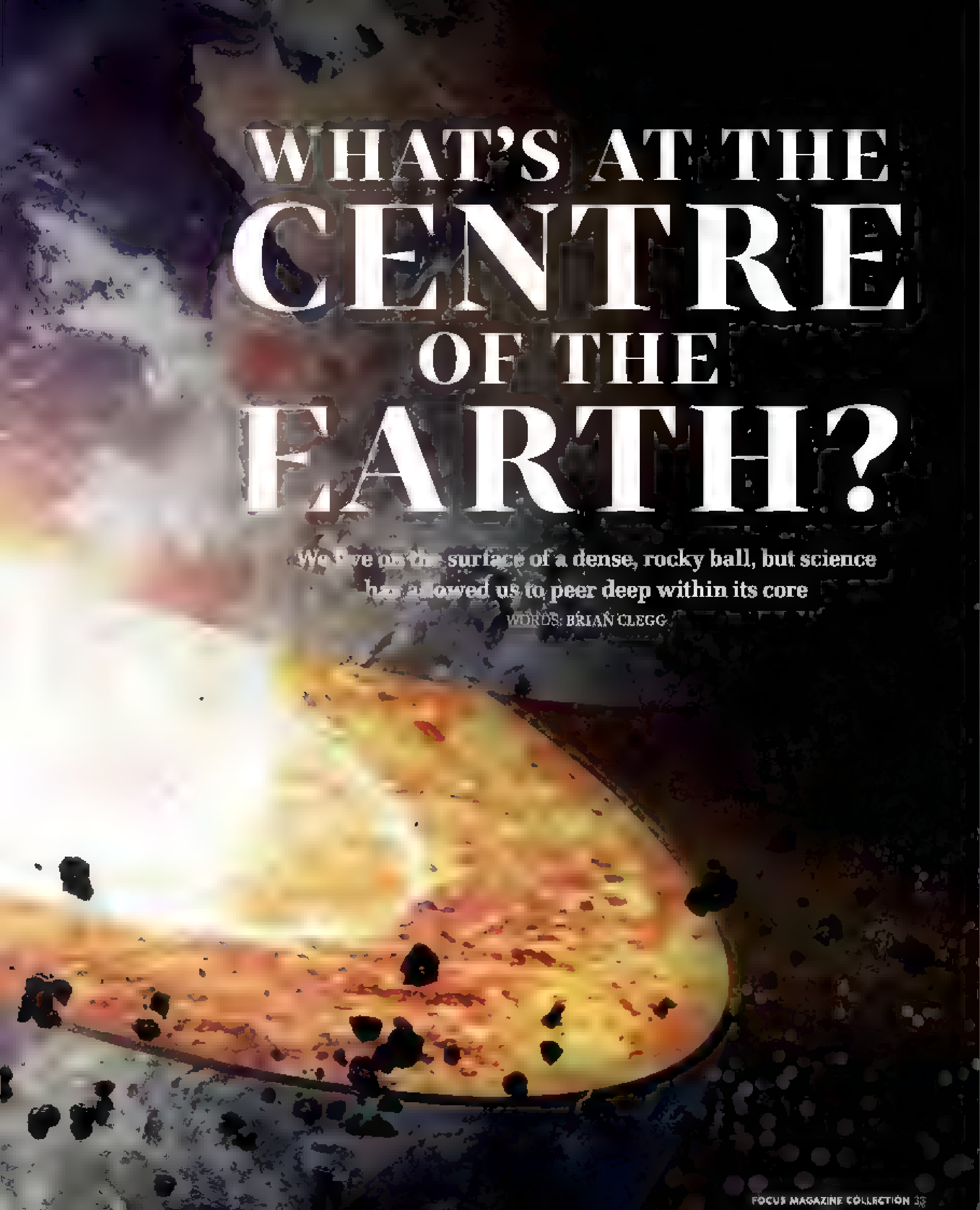
If you suffer from arachnophobia, relax. These knobbly-kneed creatures aren't actually spiders but a separate class, known as pycnogonids. They've been around for hundreds of millions of years, and simplicity is the key to their success. "They're all legs and no body," says Bray. They have no gills or digestive organs, and use a proboscis to suck the juices from anemones. Tiny sea spiders inhabit rock pools around the UK, but down in the deep, giants like these can have 60cm leg spans. They walk across the seabed and occasionally drift spread-eagled on the current. Males carry fertilised eggs glued to their bodies.

◀ COFFINFISH

The coffinfish sucks in water and blows itself up like a balloon when it feels threatened. This makes it appear bigger so predators might leave it alone (pufferfish use the same tactic). Similar fish have been found elsewhere in the deep sea, including around Indonesia, Japan and Hawaii. But this is the first sighting in Australia. To find out whether it's the same species Bray will need to X-ray it and possibly sequence its DNA. "It would be really cool if it's actually new," she says.

Dr Helen Scales (@helenscales) is a marine biologist, writer and broadcaster. Her next book, *Eye Of The Shoal*, is out in May 2018.


EXPLORING
EARTH



WHAT'S AT THE CENTRE OF THE EARTH?

We live on the surface of a dense, rocky ball, but science has allowed us to peer deep within its core

WORDS: BRIAN CLEGG

When science fiction writer Jules Verne wrote *Journey To The Centre Of The Earth* in 1864, he probably knew that his plot was pure fantasy. Verne's characters Otto, Axel and their guide Hans, only made it a few miles down, but the idea that anyone could even contemplate travelling to the Earth's core had been dismissed before Victorian times.

The idea of the Earth having a meaningful centre goes hand-in-hand with the planet being shaped like a ball, and we've known that we don't live on a disc for a long time. It's a myth that medieval folk thought the Earth was flat – this actually came from a mix of Victorian anti-religious propaganda, and a misinterpretation of the stylised maps of the period. It was over 2,200 years ago that Greek polymath Eratosthenes first measured the distance around the Earth's sphere, and it's been clear ever since that it must have a centre.

It's a myth that medieval folk thought the Earth was flat – a mix of anti-religious propaganda and misinterpretation of stylised maps

This doesn't mean, though, that early philosophers thought of Earth as we do today. Ancient Greek physics said that the world consisted of a series of concentric spheres of four fundamental elements: earth, water, air and, finally, fire. In this idea, the centre of the planet had to be solid, as air couldn't be inside the sphere of earth. Clearly, the sphere of earth wasn't completely surrounded by water or there would be no dry land, so there was thought to be a bit of the earth sticking out, meaning there could only be one continent. As a result, the discovery of the Americas was a significant step on the way to disposing of Ancient Greek science.

The idea of the Earth being entirely hollow, or with vast caverns reaching to the centre as in Verne's book, has been popular since ancient times. But it's not clear that any scientist apart from the astronomer Edmond Halley, who proposed a hollow Earth to explain some unusual compass readings in 1692, has ever taken this idea seriously. And in 1798, an English scientist and eccentric put the final nail in the coffin of the 'hollow Earth' hypothesis. This was when Henry Cavendish 'weighed' the planet.

Cavendish was an odd man, who only communicated with his servants via notes to avoid meeting them face-to-face. Despite his aristocratic background, Cavendish dedicated his life to science, working in both chemistry and physics, and most famously devised an experiment to calculate the density of the Earth.

Using a simple torsion balance, which measured the amount of twisting force caused

Misinterpreted maps from the medieval period partly led to the myth that people once thought the Earth was flat

by the gravitational pull of two large balls on a smaller pair, Cavendish was able to calculate the faint gravitational attraction between the two pairs of balls. By comparing this with the Earth's own gravitational pull, he could work out the planet's density (and, as the Earth's size was already known, its mass, too). But the density figure showed that our planet must be mostly solid, unless there were extremely dense unknown materials somewhere in the depths.

Today, we split the innards of the Earth into three segments: the crust (5-75km thick), the mantle which extends to a depth of around 2,900km, and the core – the bit we're interested in here – extending around 3,500km out from the Earth's centre, with two distinct segments. At the core's heart is an extremely hot but still solid nickel-iron sphere with a radius of around 1,200km. At approximately 5,400°C, this inner core is similar in temperature to the surface of the Sun. The remainder is the liquid outer core, also mostly nickel-iron, with similar temperatures, getting hotter towards the centre. But how can we possibly know such detail about a location that is so inaccessible? Through analysing earthquakes.

After a quake, seismic waves travel through the Earth, changing their form and direction depending on the materials they pass through. Geophysicists have used this information to deduce what lies at the Earth's core. Their seismometers, devices to measure such waves, are the equivalent of telescopes for exploring the Earth's interior.

Charles Richter confirmed Inge Lehmann's theory that the Earth had a solid core; he also created the Richter Scale to define the magnitude of earthquakes

THE KEY DISCOVERY

SCIENTIST **Inge Lehmann**

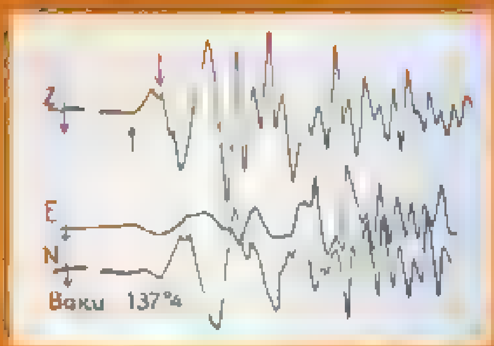
DATE **1929 to 1936**

DISCOVERY **Earth has a solid inner core**

On 17 June 1929, at around 10.17am local time, a 7.3-magnitude earthquake struck the South Island of New Zealand. Waves from the quake were recorded on seismometers around the world, notably in Frankfurt, Copenhagen, Baku, Sverdlovsk and Irkutsk. These devices consisted of a heavy weight suspended from a frame. When the Earth and the frame vibrated, the inertia of the weight prevented it from moving with them, creating a difference in motion that could be captured by a pen on a rolling sheet of paper.

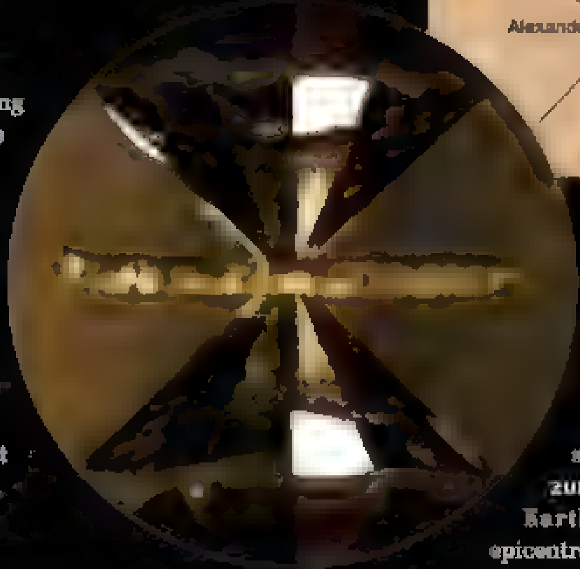
The first accurate seismometers responded to up and down movements in a horizontal arm but shortly before the New Zealand earthquake, a new kind of seismometer using a vertically suspended weight came into play, and these proved crucial in the discovery.

Danish seismologist Inge Lehmann had been working for a couple of years comparing the output of seismic stations, initially working with published data, and then going to the original records as "published readings were not always satisfactory". Lehmann discovered oddities in the wave patterns. She realised that seismic waves arriving between around 104° and 140° from the epicentre had interacted with a solid inner core, disproving the previously accepted belief that the Earth's core was entirely liquid.



Lehmann investigated seismometer recordings of a New Zealand earthquake in 1929 and found that some of the waves must have interacted with a solid core

Modern seismometer showing activity during a volcanic eruption



By the early 20th Century, increasing temperatures as we dug deeper into the Earth, combined with seismologists' analysis of earthly waves, suggested that the inner parts of our planet were at least partly molten – hot enough to turn rock and metal into liquid. The key discoveries were made by two scientists who were never even nominated for a Nobel Prize: British geologist Richard Oldham and Danish seismologist Inge Lehmann.

WONDERFUL WAVES

Seismic waves that cause damage in an earthquake travel on the surface. But there are also two types of 'body wave' that move through the Earth. P-waves ('P' stands for 'primary') are longitudinal waves, just like sound. They vibrate in the direction of movement, causing the Earth to squash up and expand as they pass through. P-waves travel rapidly – around 5km per second in a rock like granite, and up to 14km per second in the densest parts of the mantle. The second type of body wave, S-waves ('S' stands for 'secondary'), are slower, transverse waves, moving from side-to-side. Unlike P-waves, they can't travel through a liquid, which is why these two types of wave helped us understand the Earth's core.

Imagine there's a huge earthquake. Waves begin to move through the Earth. The P-waves shoot ahead, while the S-waves follow behind at around half the speed. Both types of wave will be detected by seismometers, which are used to measure vibrations in the ground, all over the Earth. But where the waves pass through the core to reach a distant measuring station, there is a so-called 'shadow zone'. Travel about 104° around the Earth's perimeter from the quake's epicentre and the waves disappear. But from 140° onwards, the P-waves reappear, with no accompanying S-waves.

As early as 1906, Oldham recognised the implications of this odd shadow. He realised that the observed P-wave and S-wave behaviour could be explained if the centre of the Earth was liquid. In such a case, P-waves would be refracted by the liquid, bending as light does when it moves from water to air, leaving a distinctive shadow. S-waves, by contrast, would be stopped entirely by a liquid core.

Oldham's breakthrough led to a widely accepted picture of a molten core, but 30 years later, Inge Lehmann realised that Oldham's idea was too simple. The refraction of the P-waves by the dense liquid in the centre of the Earth should have produced a total shadow. However, measurements made with the more sensitive seismometers available by Lehmann's time showed that faint P-waves were still arriving

TOP: Eratosthenes' knowledge of the Sun and given locations on the planet helped him calculate Earth's circumference

ABOVE: In a diamond anvil cell, metals are squashed between two diamonds at enormous pressures, to simulate conditions at the Earth's core

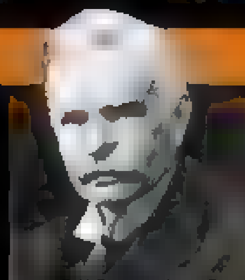
TIMELINE: UNDERSTANDING THE EARTH'S CORE

Scientists managed to find out what is at the centre of our planet, without ever picking up a spade...

1798

English scientist Henry Cavendish (1731-1810) used a torsion balance to measure the gravitational attraction between heavy balls, deducing Earth's density. In 1798, he published the results, giving the first figure for the planet's density. This figure was sufficiently high that it was unlikely the Earth was hollow.

1906



Richard Dixon Oldham (1858-1936) was a Dublin-born geologist who identified the main wave types on seismograph recordings. He deduced that the Earth had a liquid core and made an approximation of its size. In retirement, he made use of the data on arrival times of seismic waves at different points on the Earth's surface to deduce that planet Earth had a liquid core.

in the shadow zone. By studying data passing through the planet from a 1929 New Zealand earthquake (see 'The key discovery' on page 35), Lehmann proposed that these waves were being reflected off the boundary between an inner solid core and the outer liquid. Her results, published in 1936, were confirmed two years later by Beno Gutenberg and Charles Richter, who accurately modelled the effects of a solid core. Direct measurements of these reflected seismic waves finally came in 1970.

UNDER PRESSURE

Further studies picked up even more subtle waves which, from their delayed arrival, had to have crossed the liquid outer core as P-waves, before being converted to transverse S-waves in the inner core, and then back to P-waves on the way out. This discovery, only confirmed in 2005, was further proof of the solid core.

Even so, the exact nature of the inner core is subject to significant debate. Temperatures, for instance, can only be worked out from experimental studies of how materials melt and solidify under pressure. And the assumption that the core consists primarily of iron and nickel comes from a combination of the frequency with which different elements occur in our local region of the Milky Way, and our understanding of how our planet formed.

Under the immense pressure at the centre of the Earth – over three million times atmospheric pressure – materials can act very differently from normal conditions. While the most obvious contender for the inner core is

Under the immense pressure – over three million times atmospheric pressure – materials act very differently

a solid nickel-iron alloy, it is possible for an extremely dense plasma – the state of matter found in a star – to have similar properties. One of the difficulties here is knowing how materials behave in such extreme environments.

Enter the diamond anvil cell. In this remarkable device, the points of two diamonds, just a fraction of a millimetre across, are squeezed together. Applying a force to a small area produces more pressure than applying it to a wide one – that's why being trodden on by a stiletto heel is much more painful than a flat sole. The diamond anvil creates pressures up to twice that of the Earth's core, and heating is applied using lasers. When metallic samples are crushed and heated to core-like conditions, the results suggest a crystalline solid in the centre of the Earth.

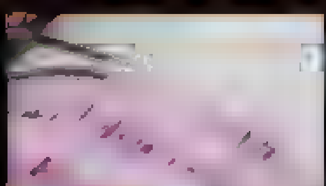
Realistically, we will never get anywhere near the Earth's core. The levels of heat, pressure and radioactivity (one of the main sources of internal heating) are so high that even if we could bore through over 6,000km of rock and metal, a probe would be unable to survive. But our planet's own vibrations, produced by earthquakes, give us the means to explore with our minds where we will never visit in person. ●

Brian Clegg is a science writer. His most recent book is *Gravitational Waves: How Einstein's Spacetime Ripples Reveal the Secrets of the Universe*

Listen to an episode of *In Our Time* about the Earth's core at bbc.in/1zdcaKF

1936

Danish seismologist and geophysicist Inge Lehmann (1888-1993) interpreted the P-waves in the 'shadow zone' as reflections from a solid inner core within the liquid core of the Earth. Despite this breakthrough on the structure of the Earth's core, notably after the 1929 New Zealand earthquake, Lehmann was never awarded a professorship.

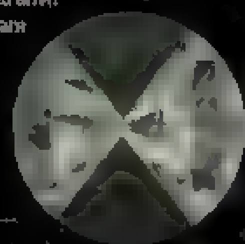


1938

Beno Gutenberg and Charles Richter confirmed Lehmann's theory, working backwards from the idea of a solid core to see what size would produce the timings used by Lehmann.

2011

Kei Hirose (1968-) from Toyko Institute of Technology is a leading researcher into the Earth's deep interior. Using diamond anvil cells, Hirose and his team have attempted to recreate conditions at the Earth's core, putting nickel-iron alloy under extreme pressure and raising it to 4,500°C.



MISSION MOHOLE

Drilling to the edge of Earth's mantle

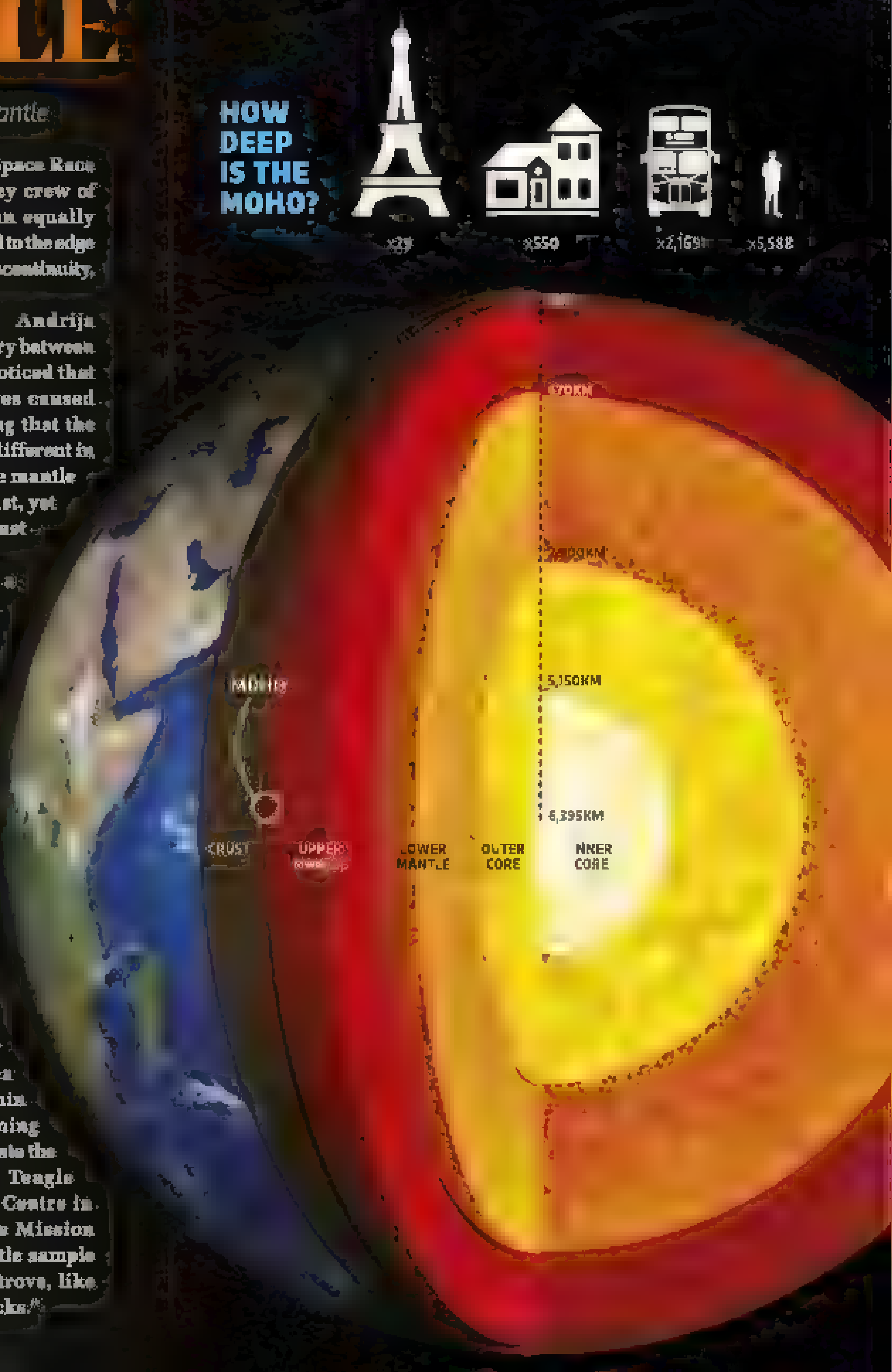
Back in the '50s, while the Space Race was in full swing, a motley crew of scientists came up with an equally ambitious project. They wanted to drill to the edge of Earth's mantle – the Mohorovičić discontinuity, nicknamed the Moho.

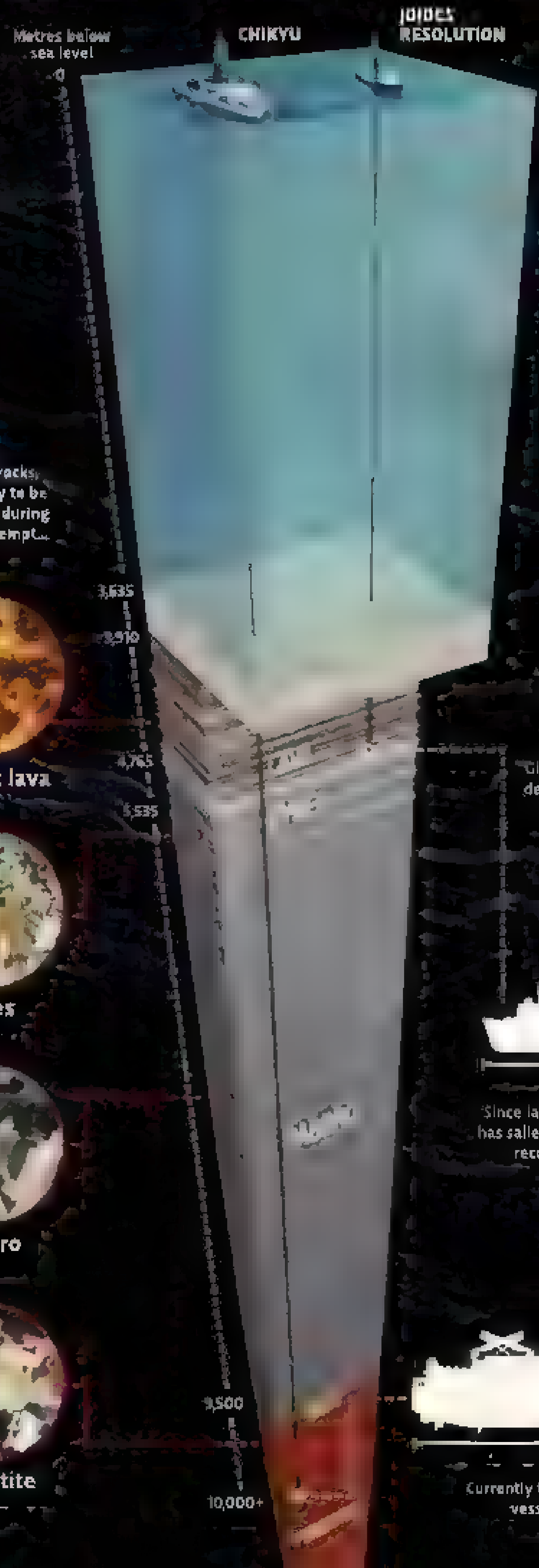
In 1909, Croatian geologist Andrija Mohorovičić discovered the boundary between our planet's crust and mantle. He noticed that around 30km down, seismic waves caused by earthquakes sped up, suggesting that the rocks down there were completely different in composition. We now know that the mantle lies 30-60km below continental crust, yet only around 5km below oceanic crust – within reach of drills.

The first drilling mission was a success – boring to a depth of 183m. But then politics played a lethal hand, funding was cut and Project Mohole was canned.

Picking up where Project Mohole left off is Mission Mohole. The International Ocean Discovery Program (IODP) plans to drill all the way to the Moho using the research vessel Chikyu, which costs around $500k a day to run. So far, it holds the record for the deepest scientific ocean drilling – roughly 3km below the sea floor.

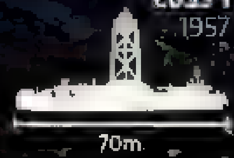
So, still a few kilometres off Moho depth. Even then, it'll be a challenge to keep the ship steady – hovering over one spot as the sea swells and ebbs. "Like lowering a thin hair into a two-metre deep swimming pool, and then drilling three metres into the foundations," says Prof Damon Teagle from the National Oceanography Centre in Southampton, who is part of the Mission Mohole team. "But a pristine mantle sample would be a geochemical treasure trove, like bringing back the Apollo lunar rocks."





DRILLING SHIPS

CUSS 1
1957



The first deep-sea drilling ship, built by oil companies and used in the first attempt to drill into the Moho in 1961.

GLOMAR CHALLENGER
1968

Glomar Challenger provided the first definitive proof of plate tectonics, as well as some key insights into the nature of Earth's crust.

JOIDES RESOLUTION
1985

Since launching in 1985, JOIDES Resolution has sailed on 132 scientific expeditions and recovered over 251kg of core samples.

CHIKYU
2005

Currently the world's most advanced drilling vessel, Chikyu displaces 56,752 tonnes.

CRUST

The outer layer of our planet is relatively thin, between 0-60km thick. Sediments at the surface lie on top of lavas, which sit above gabbros – igneous rocks. Continental crust is much thicker than oceanic crust, which can be only around 5km deep in places.

MOHOROVIČIĆ DISCONTINUITY (MOHO)

This boundary between the crust and the mantle lies about 5km below the sea bed. At the Moho, it's thought rocks change in composition from crustal rocks to mantle ones.

MANTLE

The mantle makes up 68 per cent of Earth's mass, making it the largest component of our planet. The upper mantle is composed of hard rocks, while the lower mantle rocks are softer and beginning to melt.

OUTER CORE

Made of iron and nickel, we know the outer core is liquid, as seismic waves travel through it more slowly than through solid parts of our planet. The dynamo theory suggests that heat radiating from the inner core, combined with Earth's rotation, causes the liquid iron to rotate, creating weak magnetic forces.

INNER CORE

Also made of iron and nickel, the inner core is solid. With temperatures reaching up to 5,500°C, it's the engine room of Earth.

ROCKS

Some of the rocks that are likely to be encountered during the Moho attempt...

Basaltic lava

Dykes

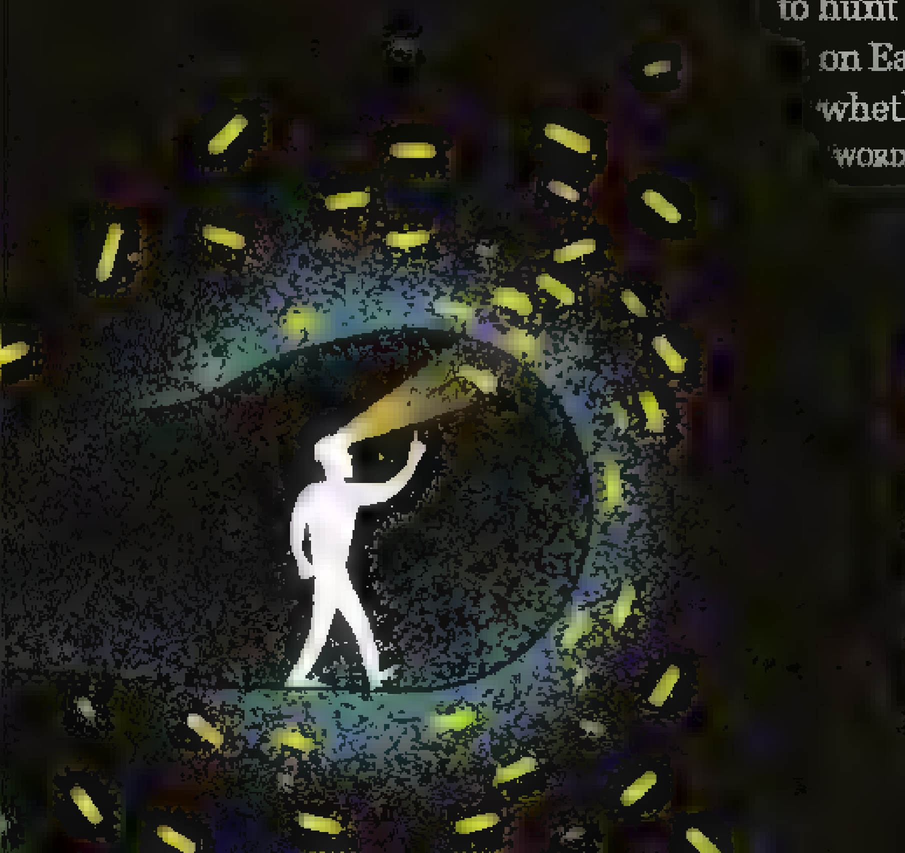
Gabbro

Peridotite

LIFE ON THE EDGE

Scientists are venturing deep underground to hunt for bugs that could explain how life on Earth began, and may offer clues as to whether alien life exists on other planets

WORDS: JHENI OSMAN ILLUSTRATIONS: JAMES OLSTEIN



Armed with a head torch, canisters and electrodes, Yamini Jangir waits as the lift descends into the darkness. Dank air closes around her. She passes roughly hewn layers of rock, hacked back years ago to make way for the lift shaft.

The lift cage eventually judders to a halt, 1.5km below the surface. Picking her way along the gold mine's maze of passages, she finally locates an old metal pipe. Siphoning off the water inside, she inserts the electrodes and waits for her prey to 'bite'.

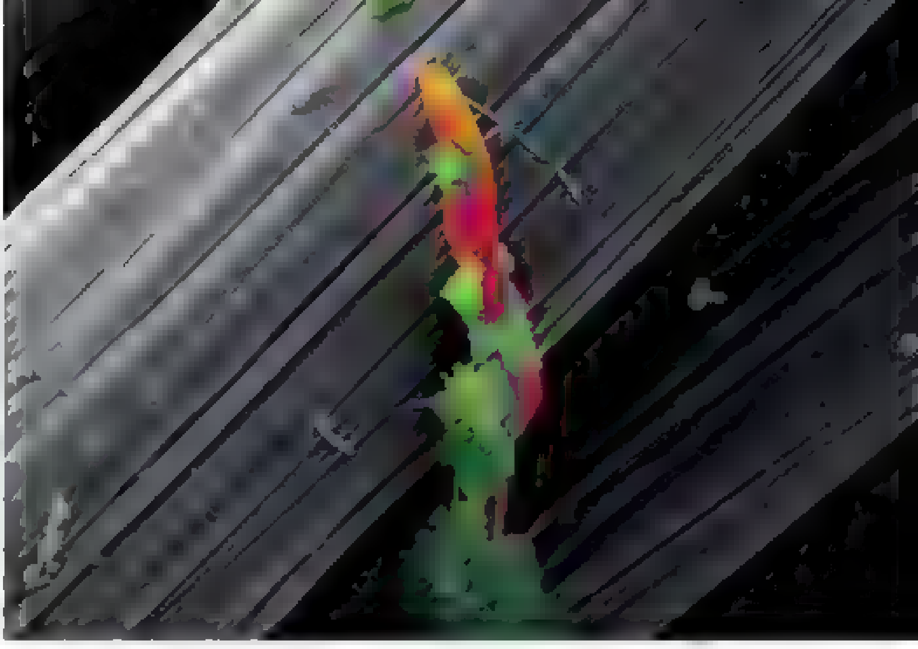
The airless, dark depths of a gold mine in South Dakota might not seem like the best place to look for life. But here, deep under the surface, microorganisms surviving on electricity alone could hold

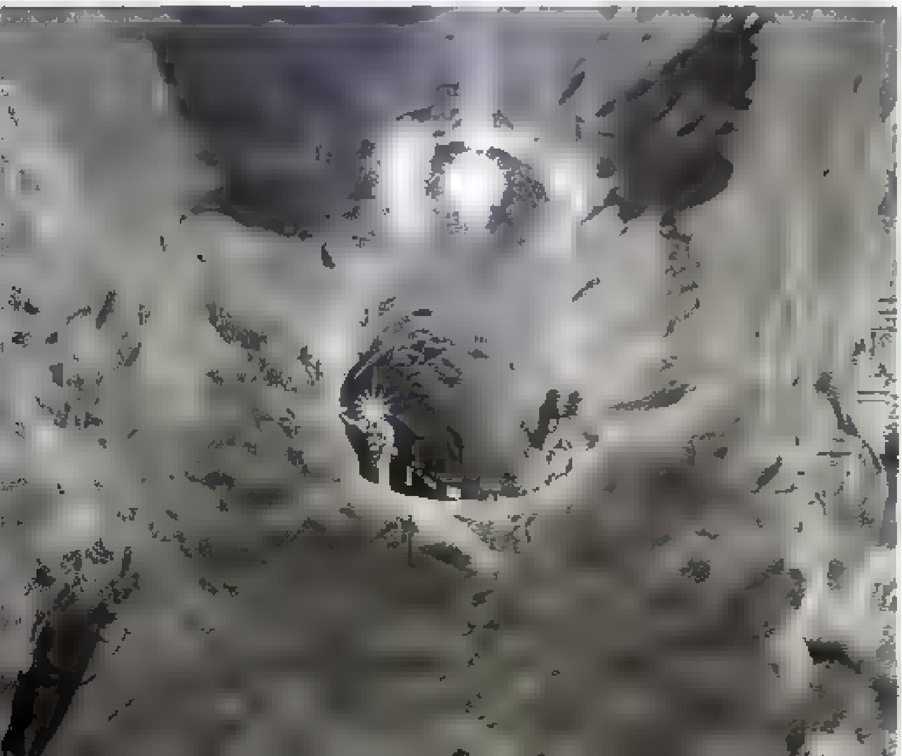
clues as to what kick started life on Earth and where aliens might exist elsewhere in our Solar System and beyond

THE POWER OF LIFE

Laptops, smartphones and other electronic devices rely on electricity, specifically the flow of electrons. Electrons are found in all atoms, and are the negatively charged subatomic particles that carry electricity through solids.

But electron flow isn't just limited to gadgets and appliances. It's also vital for living cells. Our cells, our organs and our entire bodies are powered by the movement of electrons, which are present in the atoms of the food we eat. Food is an 'electron donor' – the power supply. But for these electrons to flow, something needs to be drawing on the supply. Oxygen, an 'electron acceptor', scavenges these electrons from other molecules during chemical reactions, therefore generating a flow. The actual process is more nuanced than this but, at its core, this is how all living things are powered. The microorganisms, lurking in the deep, dark places of the world, seem to have harnessed the ability to directly consume electrons from their environment – they have a direct line. "All life essentially feeds off electricity," explains Jangir's supervisor Prof Moh El-Naggar from the University of Southern California. "But microbes have managed to take it to the next level."





ABOVE This electrode (grey) was left underground for five months and attracted electron-eating microbes (orange)

BELOW The Sanford Underground Research Facility offers an intriguing space for scientists to hunt for unusual microbes

METAL MUNCHERS

Microbes like the ones El-Naggar and his team are studying were discovered decades ago. Back in the 1980s, researchers found that two species, *Shewanella* and *Geobacter*, were able to survive without the oxygen to generate the flow of electrons. Instead, the bacteria used metal-based minerals, such as iron- or manganese-based rocks, as 'electron acceptors' to produce an electron flow when oxygen wasn't present in the environment. Since then, different research groups have discovered more of these microbes, and found that the bacteria weren't just able to 'dump' electrons directly into minerals – they were able to pick them up too. In other words they were feeding directly from the minerals by creating a living circuit.

No one knows exactly how many of these electron-eating species there are, but scientific research suggests it's a fairly widespread ability in many kinds of microbes. However, the microbes are most likely to be found in extreme environments that are rich in insoluble substrates. "Deep underground is an obvious place for the electron-eating microbes to live, where the rocks contain elements, such as sulphur and iron, which easily lose or gain electrons," says Jangir. "But microbes are extremely versatile and use all sorts of methods to survive. Depending on the environment, some use multiple electron donors and acceptors. For example, the microbe that picks up electrons from electrodes may be perfectly capable ▶

YAMINI JANGIR, PROFESSOR MOH EL-NAGGAR, KEN KARP, SANFORD

HOW MICROBES FEED ON ELECTRICITY

Every organism gains its energy by the flow of electrons from an electron donor to an electron acceptor. In humans and other animals these electron donor and acceptor molecules are free to diffuse *inside* our cells, where they synthesise the 'energy currency' of cells, adenosine triphosphate, in the power stations of the cells.

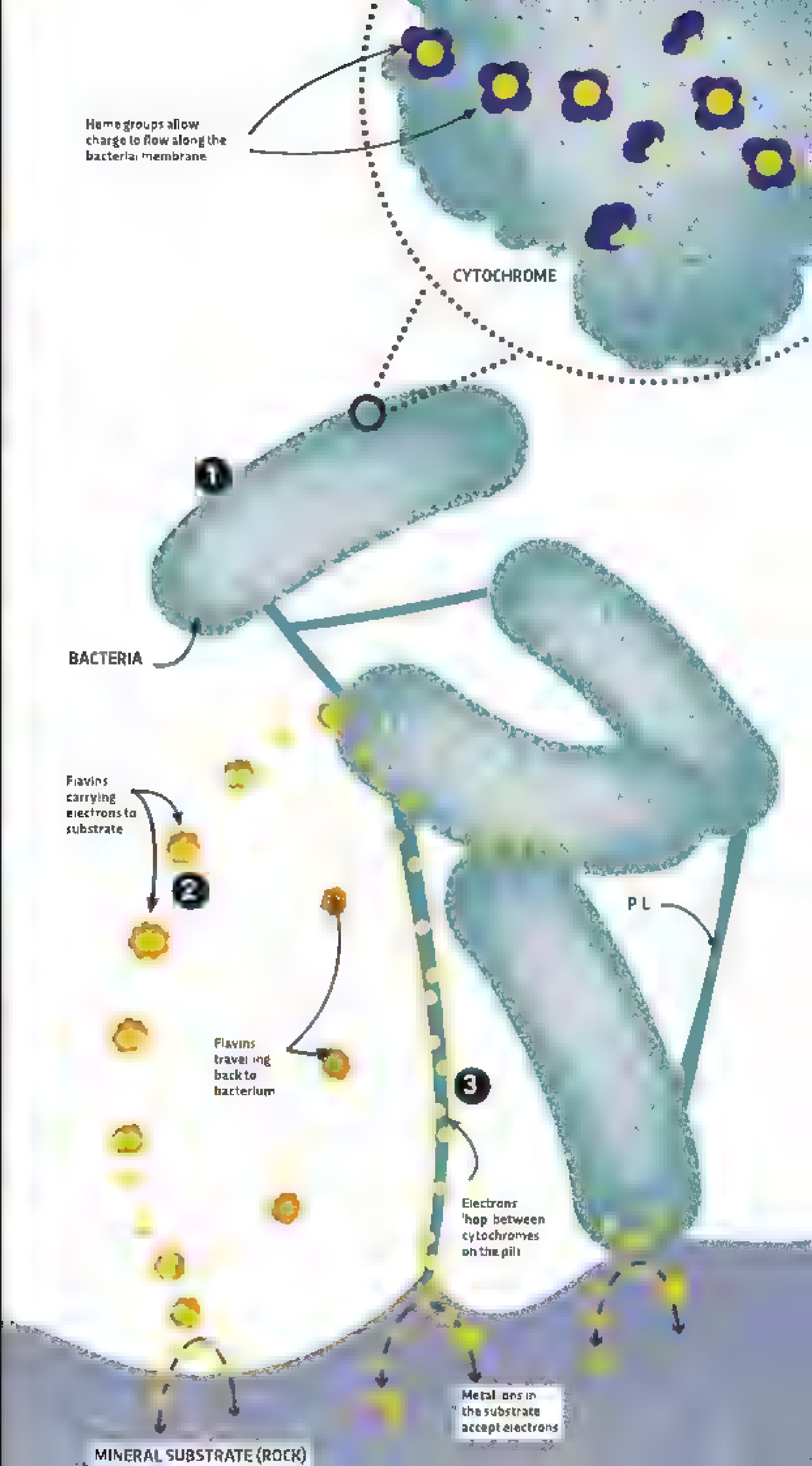
The same process happens in single-celled organisms (such as archaea and bacteria), but the electron transfer also occurs *outside* the cell. The microbes that feed on electricity alone transfer electrons to metal oxides, such as iron and manganese minerals in rocks, either by electron-shuttles called 'flavins' or along nanowires known as 'pili'.

Key:

❶ Cytochromes are proteins that are present on the outer membrane of the bacteria. Cytochromes contain 'heme groups' that accept and donate electrons, enabling charge to flow along the membrane.

❷ Molecules called flavins act as electron shuttles, picking up electrons from the cell and dropping them off at a nearby electron acceptor, such as a mineral substrate. Once the flavins have dropped off the electrons, they travel back to the bacteria to collect some more.

❸ Electrons can also travel along nanowires, called 'pili', sticking out of the microbe cell body. The pili are also covered in cytochromes, and the electrons use them to 'hop' along the nanowire.



A MARVELLOUS MICROBIAL MENU

The strange eating habits of some of the world's most bizarre bugs

POTTY MOUTH

Microbes are often used to break down waste at sewage treatment plants. *Brocadia anammoxidans* can survive without oxygen and loves nothing better than to lunch on ammonia and nitrate in human waste, producing a fuel that could, theoretically, be used for space probes.

SLICK SOLUTION

In April 2010, the Deepwater Horizon oil rig burst into flames, spilling almost five million barrels of oil. Genetically modified *Alcanivorax borkumensis* microbes were brought in to help with the clean-up operation by breaking down the oil's molecular structure.

NUKED!

In 2014, a team from the University of Manchester discovered that various microbes can degrade the organic material found in nuclear waste. The microbes use the waste as a source of food and energy, and prevent radioactive elements leaking into the environment.

SMARTY PANTS

Stinky underwear can be a problem on any long journey – particularly if you're aboard the International Space Station. The solution? In the 1990s, Russian scientists tried using various bacteria to degrade soiled underwear and turn the resulting methane into biofuel.

PLASTIC SURGERY

Around 300,000 tonnes of plastic swirl around the planet's oceans at any one time. That is one giant plastic problem. The good news is that a team of Japanese scientists has discovered a bacterium (*Ideonella sakaiensis*) that eats the plastic found in most disposable bottles.

of using other more conventional sources of electrons. And the ones that send electrons away to surfaces might be able to use more conventional molecules to breathe, such as nitrates, sulphates and even oxygen."

EXTREMOPHILES

These metal munching microbes are just some of the many tiny, super powered organisms living in extreme environments on Earth.

So-called 'extremophiles' can survive in conditions that are hostile to other life. Take the case of the *Aquifex* genus of bacteria, which lives in hot springs in Yellowstone National Park, where temperatures can reach 96°C. Or the salt loving *Halobacterium halobium*, which survives in sediments that are 10 times saltier than seawater. And then there is 'The Daddy' of all extremophiles – Conan the Bacterium (aka *Deinococcus radiodurans*), which can withstand acid baths, radiation doses and huge temperature variations.

But El Naggar and his team are intent on finding out more about the electron eating microbes in particular. They've already made some astounding discoveries about these microbes' anatomies. One day while filming *Shewanella* under a microscope, it dawned on the team that seemingly innocuous hair like appendages were in fact vital to the electron transfer system. Electrons were travelling along these 'nanowires' to the mineral substrate. And El Naggar believes that when microbes are piled one on top of another in sediment, the nanowires act a bit like straws, so that

"Electron transfer is fundamental to all of life's energetics. Perhaps it holds the key to discovering life on other planets"

the microbes at the bottom of the pile can still transfer electrons

Until a few years ago, the team studied the microbes in a lab setting, because they wanted to use physical electrodes in place of the electron donors or acceptors that these organisms interact with in nature.

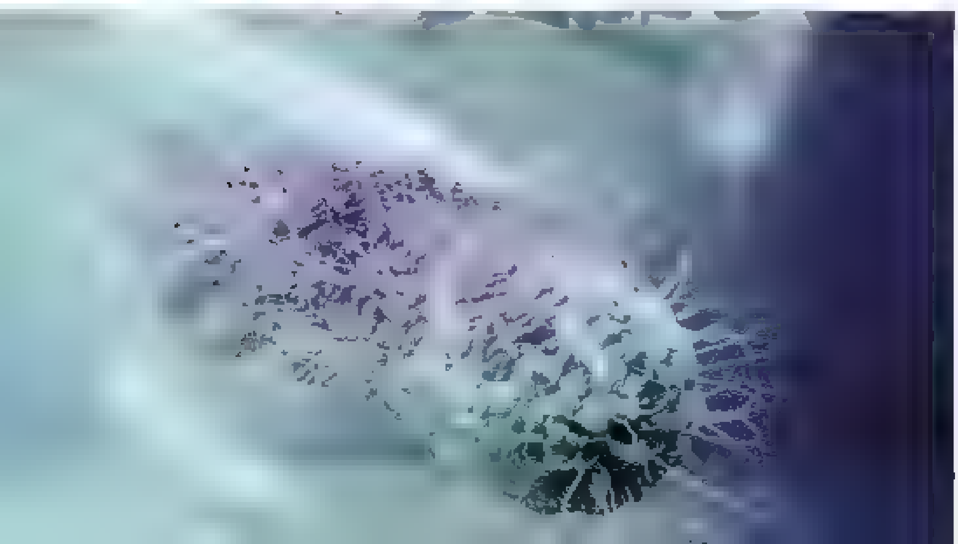
"Electrodes give a huge advantage since they don't get consumed and allow physical interrogations of the mechanisms by changing electric potentials and so on," says El-Naggar. "We don't yet understand the movement of electrons in biology as well as we understand them in metals or semiconductors," says El-Naggar. "Yet look at the amazing developments of our digital age that were enabled by an understanding of how electrons move in 'hard materials'."

Microbes that transfer electrons have already been used for tasks such as degrading toxic and industrial waste, and recovering metals. Scientists are now looking at how to harness microbial electron transfer to synthesise nanomaterials, and are working on technologies that use microbes to generate electricity.

But, crucially, El-Naggar and his team believe that their research might reveal clues as to how life developed on Earth and how it could have evolved on other planets.

BELOW LEFT New York State's Oneida Lake is where *Shewanella*, one of the original electron-eating microbes, was discovered in the 1980s

BELOW RIGHT The long, hair-like structures on *Shewanella* are an important part of its electron transfer system



HUNTING FOR ALIENS

Every day, each of us takes around 20,000 breaths. We take it for granted that there's oxygen in the atmosphere. But billions of years ago breathing wouldn't have been possible, as oxygen didn't exist. About 2.3 billion years ago, Earth's atmosphere radically changed. In this so-called 'Great Oxygenation Event' (GOE), marine cyanobacteria started to produce oxygen by photosynthesis, which led to the development of organisms that could use oxygen to generate energy.

Before the GOE, microbes had to get their energy from elsewhere, and one source was minerals. Indeed, one theory for how life developed from Earth's primordial soup suggests it developed on mineral surfaces that concentrated biological molecules and catalysed reactions. The discovery that these microbes can transport electrons into their cells from mineral surfaces could fill in the missing link in that theory and may provide clues as to how life could exist on other oxygen-deficient planets.

"While the surface conditions of many planetary bodies seem inhospitable, it's possible that life either used to exist, or now exists, underground or in massive ice shells," says El-Naggar. "Electron transfer is not an Earth-centric notion: it's fundamental to all of life's energetics. Perhaps it holds the key to discovering evidence of life on other planets!"

Astrobiologist Prof Lewis Dartnell, from the University of Westminster, agrees that these microbes could exist anywhere in the cosmos. "By stripping electrons off metals in rocks, such microbes could have a ready source of energy pretty much anywhere – even on Mars, where there are plenty of iron-containing minerals and pockets of liquid water underground. In fact, most lifeforms in the Galaxy might turn out not to be sunbathers like much of the life on Earth, but electron munchers!" F

Jheni Osman is a science journalist and presenter of *SciTech Voyager*. Her books include *100 Ideas That Changed The World* and *The World's Great Wonders*

ROUTE TO THE TOP OF THE WORLD

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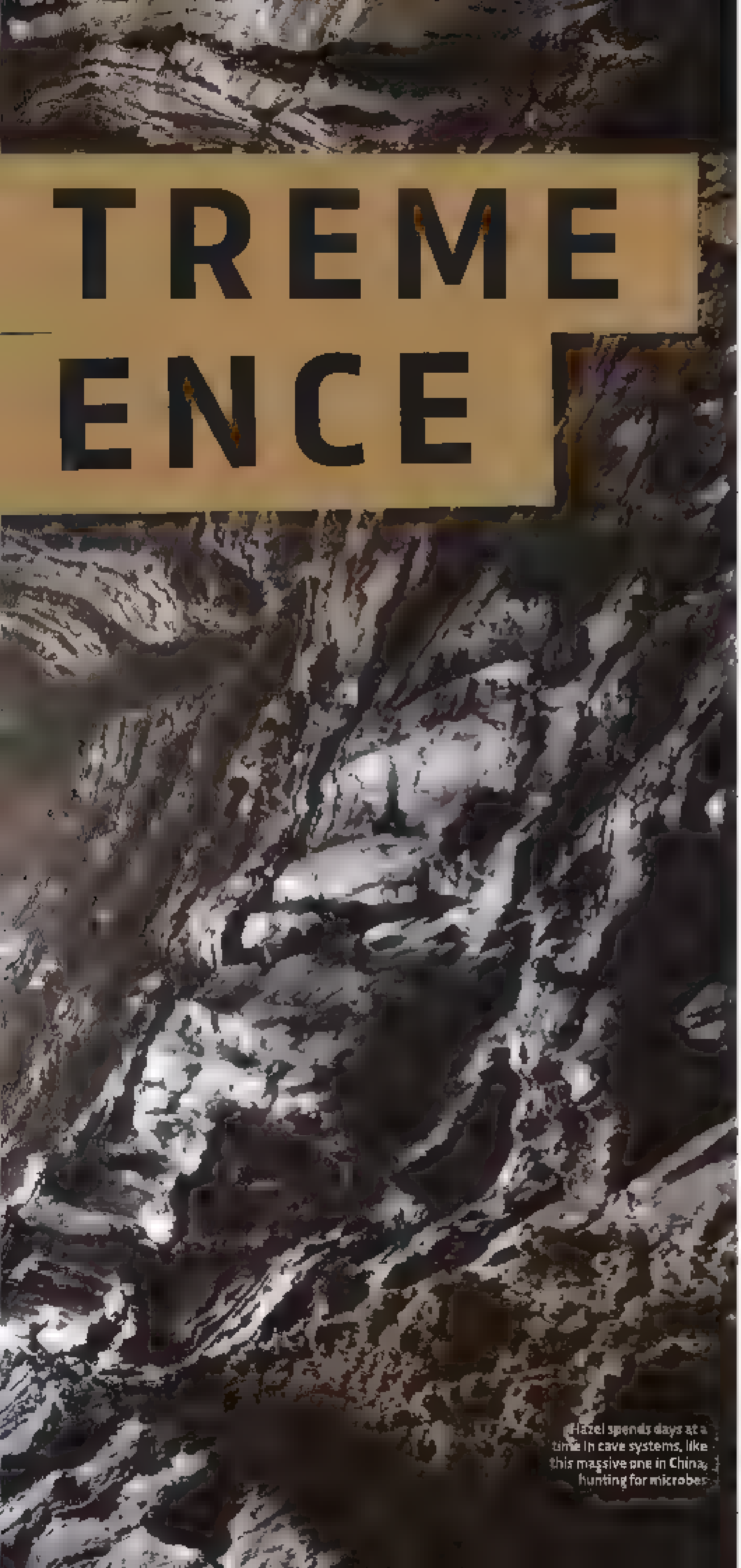
THE MOST EX
JOBS IN SCI

From dodging erupting volcanoes to battling frostbite, here are some of the most extraordinary jobs in science

WORDS: KATHERINE NIGHTINGALE AND JO CARLOWE

TREME ENCE



Hazel spends days at a time in cave systems, like this massive one in China, hunting for microbes

ROBBIE SHONE

THE CAVE RAIDER

NAME: Dr Hazel Barton
JOB TITLE: Microbiologist
BASED: University of Akron, Ohio, USA

"I started caving back in sixth form at school, long before I became a scientist. When I started working as an environmental microbiologist it seemed natural to combine the two.

I study microbial ecosystems in deep and remote caves, trying to work out how micro-organisms can grow in the dark with so few nutrients. We work at depths of up to 500m – the microbiology gets more interesting the deeper you get. We'll spend around a week in a cave, exploring its structure and taking samples of microbes. The expeditions are huge undertakings, about as logistically technical as climbing Everest. We rig our own ropes, and carry all our camping gear and research equipment, sometimes through gaps as small as 20cm.

When you spend a week in complete darkness, you have to be careful that your circadian rhythm doesn't slip into 27-hour days. I make sure that everyone's in bed by 10pm and up at 7am. On the first few trips you get really cranky because of the lack of sunlight. And you need to make sure that you like and trust the people you're with. If something goes wrong, your life is in their hands.

The best thing about my job is the travel – as well as the US, we also work in Venezuela, Brazil, Belgium and China. You never know what you're going to find. In China, we discovered the third biggest cave room in the world by following a river into a mountainside and ending up in a vast 400m-high, 600m-long space. It was incredible."

THE EXPEDITION MEDIC

NAME: Dr Alexander Kumar
JOB TITLE: Academic clinical fellow, Kings College London, UK
BASED: Guy's and St Thomas' NHS Foundation Trust, London

Dr Alexander Kumar at Concordia research station in Antarctica

"I've always had an adventurous streak, driven by an endless child-like curiosity for the world's people and places. I realised how interesting it would be to work with the poorest populations on the planet against some of the world's biggest challenges. Global health bridges my background experience in expedition, polar, space and tropical medicine.

I trained in anaesthetics, intensive care and then infectious diseases, while completing further specialist certification in high altitude, disaster and tropical medicine. In the past 18 months, I've been lucky to work in public-private partnerships with foundations, governments and on expeditions spanning over 30 countries. As an expedition medic I've worked with explorers, such as Sir Ranulph Fiennes, and in places like the Amazon and Antarctica.

I spent a year overwintering in Antarctica, working with ESA, conducting research to understand how the human body and mind could survive a return trip to Mars. I often ventured out in conditions below -80°C. If I'm on a country walk in the UK and I drop my glove, I pick it up. If my glove comes off in Antarctica, I could lose my fingers. It's the sort of weather where your headphone cables snap in half. For nine months of the year, the research station where I was based was unreachable. So, as the station's only doctor (usually there are two), if I had got appendicitis during the winter 'lock in', I faced two choices – either cut myself open or give up and face death if the antibiotics didn't work.

Antarctica is a high altitude desert, so you suffer chronic hypobaric hypoxia. And the 100 days of darkness during winter puts you through a 'washing machine' of time. But Antarctica is incredibly beautiful and I feel privileged to have had that experience."

THE LAVA LOVER

NAME: Dr Hugh Tuffen
JOB TITLE: Volcanologist
BASED: Lancaster University, UK

Heat-resistant suits protect volcanologists from searing temperatures inside craters

"I first became interested in volcanoes when I was about seven. I was so obsessed that I slept with a volcano picture book under my pillow.

There have been concerning moments. One night in Chile, heavy ash and pumice rained down on our camp and we had to decide whether to stay or go. Or there was the time we were digging increasingly desperately into the mountainside to find uncontaminated snow to melt for drinking water. I also spent months camping in Iceland for my PhD, enduring days of wind and rain. It's not much fun putting on wet clothes for the fourth day in a row, but the exquisite beauty and isolation of the environment makes up for it.

I study what makes volcanoes explosive and how the gas trapped in magma drives violent eruptions, forcing out lava and throwing ash kilometres into the air. We're also trying to figure out what controls the way that lava flows, in the hope of helping people who live in its path. This means travelling abroad to erupting volcanoes, often at short notice, to witness these explosions.

Sometimes it's possible to walk up to lava as it flows and take samples with a shovel. Back in the lab, we'll heat a sample to over 1,200°C so it'll behave like it's in the volcano. This means we can see what's happening on a microscopic scale.

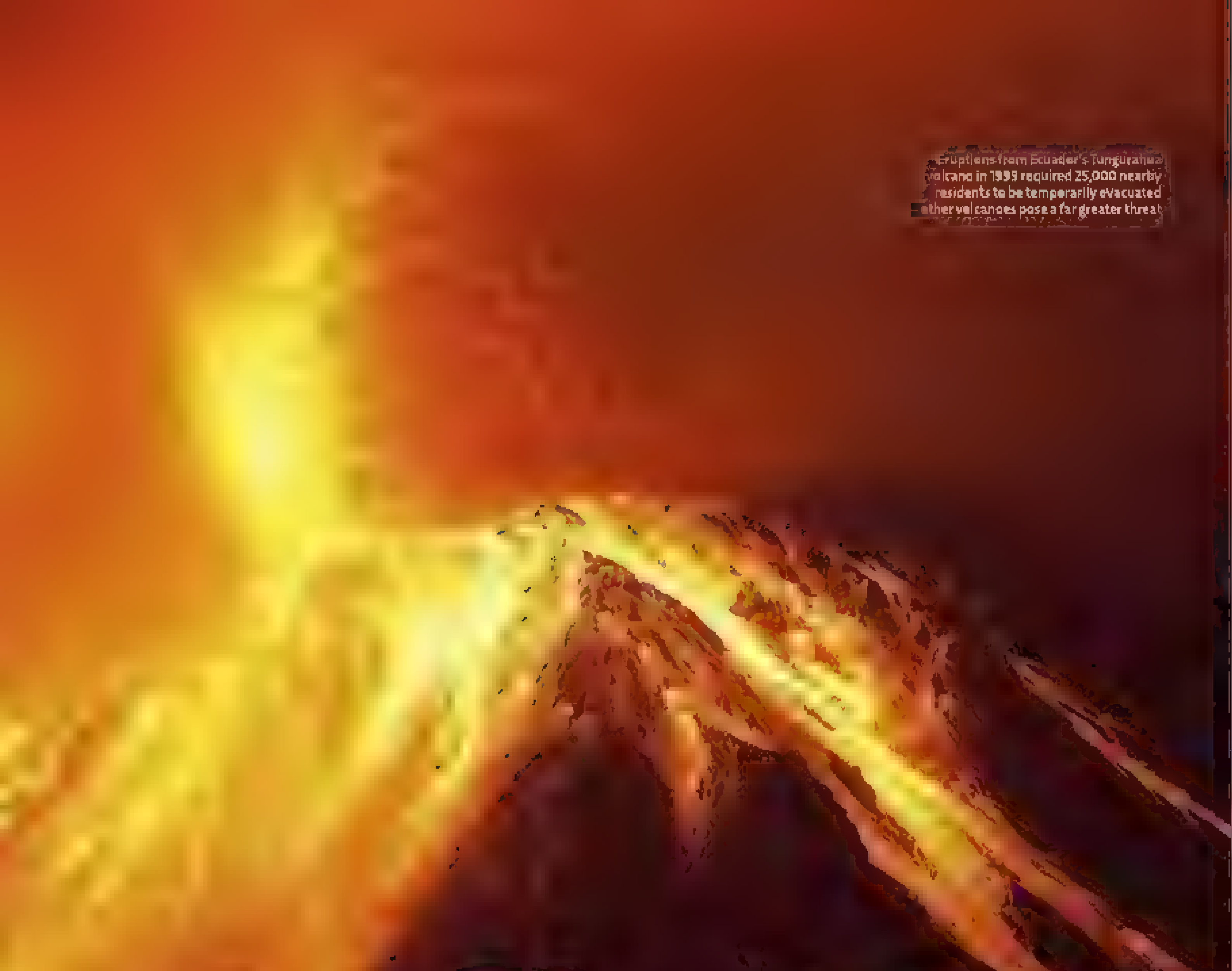
Knowing that my work can help lots of people is motivating. But it's annoying that there are far too many interesting volcanoes to study and that's before you even include the ones on other planets and moons in our Solar System."

Turn the page to find out which are the world's deadliest volcanoes

THE WORLD'S DEADLIEST VOLCANOES

Beautiful, yet potentially deadly, volcanic eruptions can wreak havoc. Find out which volcanoes scientists are keeping a close eye on

WORDS: BILL MCGUIRE

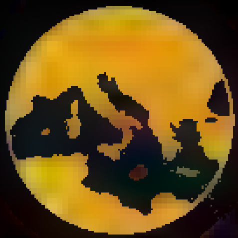


Eruptions from Ecuador's Tungurahua volcano in 1999 required 25,000 nearby residents to be temporarily evacuated – other volcanoes pose a far greater threat

Volcanoes may not, generally speaking, take as many lives as earthquakes and floods – 92,000 in the last 100 years. But the greatest of volcanic outbursts can bring about a global freeze, worldwide harvest failure and unimaginable loss of life. Around 74,000 years ago, a colossal super-eruption of the Toba volcano in Sumatra may have brought our race to the brink of extinction, while as recently as 1783, famine caused by the climatic impact of an eruption of Iceland's Laki volcano may have led to as many as six million deaths worldwide.

There are at least 1,500 active volcanoes around the world, of which around 50 erupt every year. To most people the idea of a volcano erupting equates to the outpouring of red-hot lava, but this is rarely a killer. Far more lethal are the large quantities of falling ash, the torrents of mud and debris, the towering tsunamis and, perhaps scariest of all, the hurricane-force surges of rock and incandescent gas known as pyroclastic flows.

The six volcanoes described here are adept at wreaking death and destruction in distinctive ways. What they have in common is the huge threat they present to large numbers of people and potentially – in one case – to the entire human race.



VESUVIUS

LOCATION:
BAY OF NAPLES, ITALY
LAST ERUPTION: 1944
MOST DANGEROUS CHARACTERISTIC:
MORE THAN HALF A MILLION PEOPLE DIRECTLY THREATENED BY PYROCLASTIC FLOWS AND SURGES

The excavated ruins of the Roman cities of Pompeii and Herculaneum provide awful testimony to the perilous threat presented by this twin-peaked volcano. During the famous 79AD eruption, the people living in the two communities were engulfed in the rapidly moving torrents of incandescent ash and superheated gas, known as pyroclastic flows. Death was agonising but rapid, a single breath burning the throat and destroying the lungs. The temperatures of the flows were so high that water in people's bodies turned instantly to steam, causing the skulls of the dead to explode.

Vesuvius deserves a place on the world's deadliest volcanoes list because of the sheer number of people now living nearby. Plus, the volcano is very unpredictable, in that while it can sometimes erupt almost continuously for centuries – as it did prior to its last significant outburst in 1944 – it can also lie dormant for equally long periods, which was the case in the run-up to the 79AD blast. Since the end of World War II, rapid construction, much of it unplanned or illegal, has resulted in the population of the highest-risk 'zona rossa' (red zone) exploding to more than 600,000 people. They will all be in grave danger when, as will inevitably happen at some point, Vesuvius springs to life once again.

Vesuvius can erupt almost continuously, but it can also lie dormant for long periods

Despite Vesuvius being one of the world's most closely monitored volcanoes, scientists don't know how big the next eruption will be, nor how much warning they will be able to give.

WEAPONS OF ERUPTION

The threats posed by volcanoes take many forms

Pyroclastic flows are torrents of hot rocks, gas and ash capable of obliterating all before them. They are generated when ash columns or domes of lava collapse before hurtling down the slope.

Volcanic mudflows, or lahars, are unstoppable and lethal. They are most commonly generated by heavy rain falling on loose ash, or by the passage of pyroclastic flows across glaciers.

Volcanic ash is formed by the fragmentation of ejected magma. It can damage crops severely, disrupt transport and communications and cause roofs to collapse over wide areas.

Cumbre Vieja could trigger an Atlantic tsunami

CUMBRE VIEJA

LOCATION: LA PALMA, CANARY ISLANDS
LAST ERUPTION: 1971
MOST DANGEROUS CHARACTERISTIC: CATASTROPHIC COLLAPSE OF THE VOLCANO'S WEST FLANK TRIGGERING A MAJOR TSUNAMI IN THE NORTH ATLANTIC

La Palma's Cumbre Vieja volcano is the most active in the Canary Islands. Since the 16th century, half a dozen moderate eruptions have caused damage, though casualties have been mercifully few. Looking ahead, concern is focused on a future collapse into the North Atlantic of the volcano's western flank.

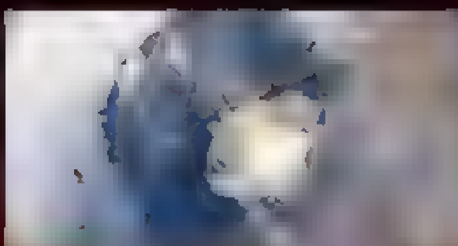
Such behaviour is uncommon, but not unheard of. Countless volcanoes reveal evidence of flank collapse at some point in their life cycles. Indeed, the Canary Island volcanoes have themselves suffered a dozen previous collapses, including one around half a million years ago that removed a massive chunk of a volcano to the north of La Palma. Now, to the south, very rapid growth since Cumbre Vieja's birth around 125,000 years ago has constructed a particularly steep-sided volcano that is ripe for collapse.

In the 1949 eruption, severe ground shaking accompanied the opening of a 4km (2.5 mile) long system of fractures along which a colossal chunk of the western half of the volcano dropped seawards by several metres. GPS monitoring reveals that this enormous detached rock mass is continuing to creep and will at some point – maybe in 10 years' time, or in 100, or in 10,000 – plunge into the ocean. Computer modelling of the event predicts the formation of a tsunami hundreds of metres high that will devastate the Canary Island archipelago in less than an hour.

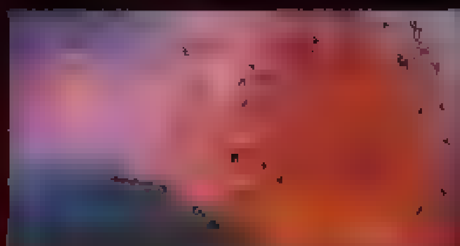
Bringing death and destruction to coastlines as far away as the UK and North America

Some scientists predict that the tsunami will remain destructive even at distances of thousands of kilometres from La Palma, bringing death and destruction to coastlines as far away as the UK and North America. But these conclusions are controversial.

Landslides result from the collapse of a volcano's flank. Rapidly growing volcanoes quickly become destabilised by earthquakes, or by magma forcing its way into the structure.



Volcanic gases, especially sulphur dioxide, are pumped into the atmosphere in vast quantities during eruptions. These gases block the Sun's heat, which can cause severe global cooling.



Volcanic bombs are solid chunks of lava blasted out during eruptions. Luckily, it's usually only volcanologists who have to dodge them since they rarely travel more than a few kilometres.

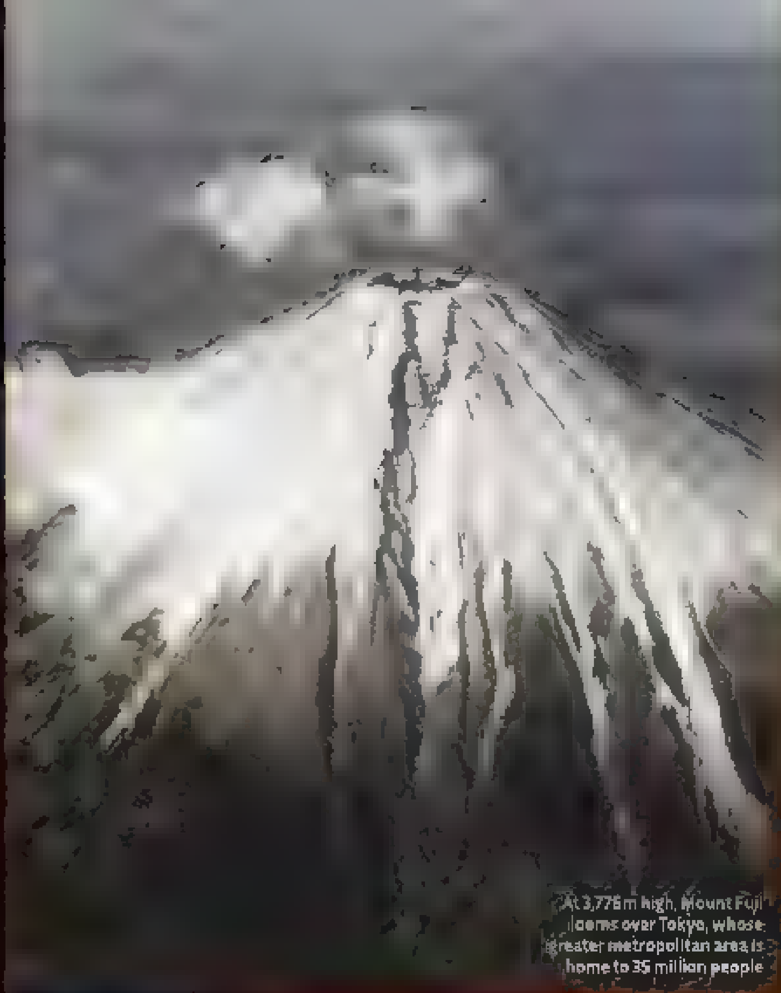
MOUNT RAINIER

LOCATION: CASCADE RANGE, WASHINGTON STATE, USA
LAST ERUPTION: POSSIBLE STEAM OUTBURST IN 1894
MOST DANGEROUS CHARACTERISTIC: FAST-MOVING MUDFLOWS CAPABLE OF REACHING INHABITED AREAS

Like Vesuvius and Mount Fuji, this monster volcano is located perilously close to an area of dense population – the cities of Seattle and Tacoma in the US. Rainier has been dormant for at least 118 years and, although past eruptions have produced heavy ash fall and pyroclastic flows, the real hazard here is mud.

Eruptions during prehistoric times resulted in the catastrophic melting of the volcano's thick ice cover, generating massive mudflows. A repeat today of the biggest could see torrents of mud wiping out several nearby towns and ploughing into downtown Seattle and the port of Tacoma.

The fact that 150,000 people live in homes built on the old mudflow deposits highlights the level of the threat, and has galvanised local government officials into planning evacuation routes and installing a mudflow early warning system. However, some communities are not convinced that enough is being done and worry that the next eruption may bring catastrophe. To add to their woes, it is perfectly possible that glaciers may melt, starting landslides – spawning large, destructive mudflows – without an accompanying eruption, and therefore without any warning.



At 3,776m high, Mount Fuji looms over Tokyo, whose greater metropolitan area is home to 35 million people

MOUNT FUJI

LOCATION: HONSHU ISLAND, JAPAN
LAST ERUPTION: 1707
MOST DANGEROUS CHARACTERISTIC: HEAVY ASH FALL ACROSS THE GREATER TOKYO METROPOLITAN AREA

Towering over the capital on the Japanese island of Honshu, Mount Fuji presents a direct threat to more people than any other volcano. This giant has been docile since its last eruption in 1707, but the 35 million inhabitants of the Greater Tokyo metropolitan area await its awakening with some trepidation.

Most of the 'Younger Fuji', built on the remains of the older volcano, is formed from quietly erupted lava flows. But the 1707 episode was far more violent, blasting out enough ash to fill Wembley soccer stadium more than 500 times over. The worry is that the next eruption could be similarly explosive.

Many volcanoes are far more proficient at vomiting great quantities of ash. The problem is that the huge extent of urbanisation in the vicinity enormously magnifies its potential impact. While the least glamorous of all volcanic hazards, the effects of the ash are manifold, and can be severely damaging: polluting water supplies, destroying crops, poisoning livestock and causing roofs to collapse. A future eruption on the scale of 1707 could dump as much as 15cm of ash across the region. The damage and economic mayhem was forecast in a Japanese government report to cost $21 billion.

GETTY X2, SUPERSTOCK, PHOTOS

Uturuncu is one of the fastest rising volcanoes in the world. An eruption there could threaten us all

UTURUNCU

LOCATION: BOLIVIA
LAST ERUPTION: 300,000 YEARS AGO
MOST DANGEROUS CHARACTERISTIC: CATACLYSMIC EXPLOSIVE ERUPTION WITH A POTENTIAL GLOBAL IMPACT

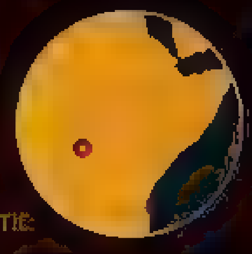
Uturuncu is a volcano so obscure that even most volcanologists had not heard of it until recently. Hidden away in southwest Bolivia, this is a volcano that has not erupted for 300,000 years. But, in 1992, radar measurements from satellites showed the volcano was starting to bulge, and the uplift has continued ever since, at a rate of 1-2cm a year over a region 70km across.

Uturuncu sits in a class of supervolcanoes that have, in the past, generated titanic, climate-modifying eruptions. Its persistent swelling may be giving us our first glimpse of a new supervolcano in the making, the next eruption of which could have a global impact.

Electrical conductivity measurements of the roots of the volcano have revealed the presence of a magma body deep beneath Uturuncu (magma is more conductive than rock), though its size has not been determined. To explain the amount of uplift, this magma reservoir must be growing at the rate of about $1m^3$ every second. No-one is suggesting an eruption is imminent – it could be many thousands of years off. But if magma continues to accumulate at the current rate over that time and is ultimately released in a single explosion, a massive amount of sulphur dioxide would be released that would form a veil across the planet, blocking out the Sun. The resulting global freeze could lead to worldwide harvest failure.

A massive amount of sulphur dioxide would be released, blocking out the Sun

NYIRAGONGO

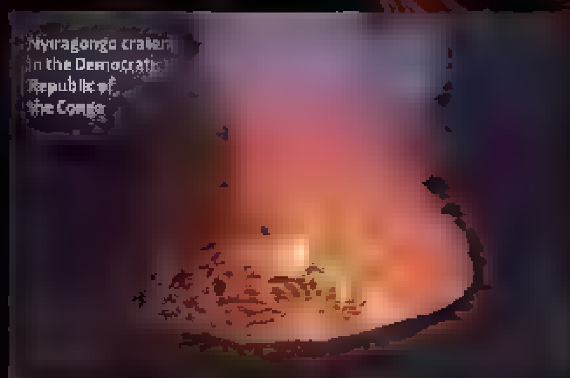


LOCATION: DEMOCRATIC REPUBLIC OF THE CONGO
LAST ERUPTION: 2002
MOST DANGEROUS CHARACTERISTIC: IT IS ONE OF THE LEAST STUDIED VOLCANOES, AS THE REGION HAS BEEN WRACKED BY CIVIL WAR

In the depths of Africa is one of the least studied (and so potentially one of the most dangerous) volcanoes of all – Nyiragongo. With a boiling cauldron of molten rock, it has the world's largest continually active lava lake.

Nyiragongo has erupted twice in the last half century, destroying the lives of people in the local city of Goma. The area is already wracked by civil war, which has ravaged the country for the last 30 years. Because of this, little research has been carried out – which makes it all the more dangerous.

Last year an international and local team of scientists mounted a major expedition to study the volcano. Four tonnes of climbing equipment, supplies and instruments were hauled up to the crater rim. Then a smaller team descended into the crater, camping for a week next to the lava lake. The aim – to hunt for signs that an eruption is brewing. Results are still being analysed, but the data should help better protect the inhabitants of Goma in the years to come. ●



Nyiragongo crater in the Democratic Republic of the Congo

Bill McGuire is *Professor of Geophysical and Climate Hazards at UCL. His latest book is Waking The Giant*

Watch a clip from *Expedition Volcano* of the team going into Nyiragongo crater: bbc.in/2EBB9Pj

"PEOPLE SAY: 'BUT YOU'RE SO OLD. WHY ARE YOU WORKING?' WELL, I WOULD PAY TO CARRY ON DOING WHAT I'M DOING!"

Sir David Attenborough talks about his illustrious career as a much-loved broadcaster and conservationist, and spills the beans on his worst-ever experience – being stranded on a remote mountain top

INTERVIEW **BEN HOARE**

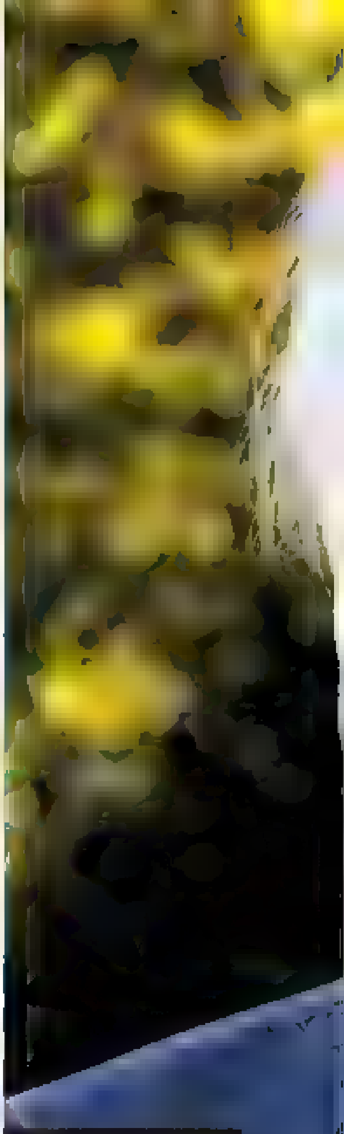
Your job is part presenter, part biologist, part conservationist, part explorer… what a fun job!
Having fun is not difficult. It's one of the few talents I have – enjoying myself. So it's obvious why you do this – you're having a ball! People say: "But you're so old. Why are you working?" Well, I'd pay to carry on doing what I'm doing!

Despite all the remote places you've visited, you live in the city
I'm a very urban man. London is the most fantastic place if you're interested in learning, music… the greatest libraries in the world are here, the greatest natural history museum in the world is here, the music is unrivalled. But I have it both ways. I can pop off to Borneo for three weeks.

What's your favourite possession?
The skeleton of a tiny crustacean called *Kiwa tyleri*. It sits on my desk. It was collected from a hydrothermal vent at the bottom of the Atlantic near South Georgia. No human could ever survive alongside this marvellous little thing.

What extinct creature would you like to meet?
The pterosaur *Quetzalcoatlus*. It was a contemporary of the dinosaurs but with wings the size of an aeroplane. We still don't really know how it took off. I personally think it was a scavenger. It had a very curious neck where the vertebrae locked and became like a long rigid pole, with its long jaws at the end of it. And I think that was in order to get inside a *Brontosaurus*. If you look at vultures now, with their long, bare-headed necks, which they push into carcasses to pull out the guts… well, if you are going to pull the guts out of a titanosaur you have to be pretty damn big.

What would your superpower be?
To fly. Not gliding, mind, I want powered flight, please! I don't just want to float around when the wind is right. I want to be able to just stretch my wings and take off. The nearest you can get to flying is underwater swimming or scuba diving. The ability to move in three dimensions is what you experience when you are scuba diving.



BELOW: Sir David holding an armadillo in 1963 for an episode of children's series *Attenborough And Animals*

What has been your worst experience in the natural world?

Being stranded on Mount Roraima in the Venezuelan rainforest – it inspired Conan Doyle's novel *The Lost World*. We were filming on the summit and we did the sensible thing, which was to go up by helicopter instead of carrying all our stuff. But this place attracts weather: it attracts clouds. And then we found we only had one tent, and there were about eight of us. And it started to rain quite heavily. There was bare rock with water sluicing across it, and we all just sat in the tent on top of one another. I remember that night very well – the torrential rain and that tiny two-man tent with all eight of us in it. At least we got the sequence. But the question is: did they use it? And the answer is no!

What is the biggest ecological change you've seen in your lifetime?

Human beings. The world population has tripled since I started making programmes in the 1950s. Tripled! In no time at all – so now wherever you go, you see human beings and the consequences of what human beings have done.

How can we deal with ballooning energy consumption?

I support the Global Apollo Programme. It is called that to make the point that if people can put a man on the Moon in 10 years, why shouldn't they be equally determined to develop a way of collecting, gathering and storing one 500th of the amount of energy that the Sun sprays on the Earth every day? If you did that, you would deal with all our power requirements.

Can we do it?

The situation is unprecedented. In the entire 200,000 year history of the human race, the whole population has never come together before. We've always been fighting our own corner. Now we have to say: "Okay, there is only one way out of this. We are all in the same boat."

Speaking of space exploration, should we be trying to colonise other planets?

No, of course not! You mean go and make a mess of them too? We don't know of anywhere where human beings can remain like human beings. They can be like bottled specimens, tied up in their own mini atmospheres, plodding about, but that's all.

"I remember that night very well – the torrential rain and that tiny two-man tent with eight of us in it"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SPACE


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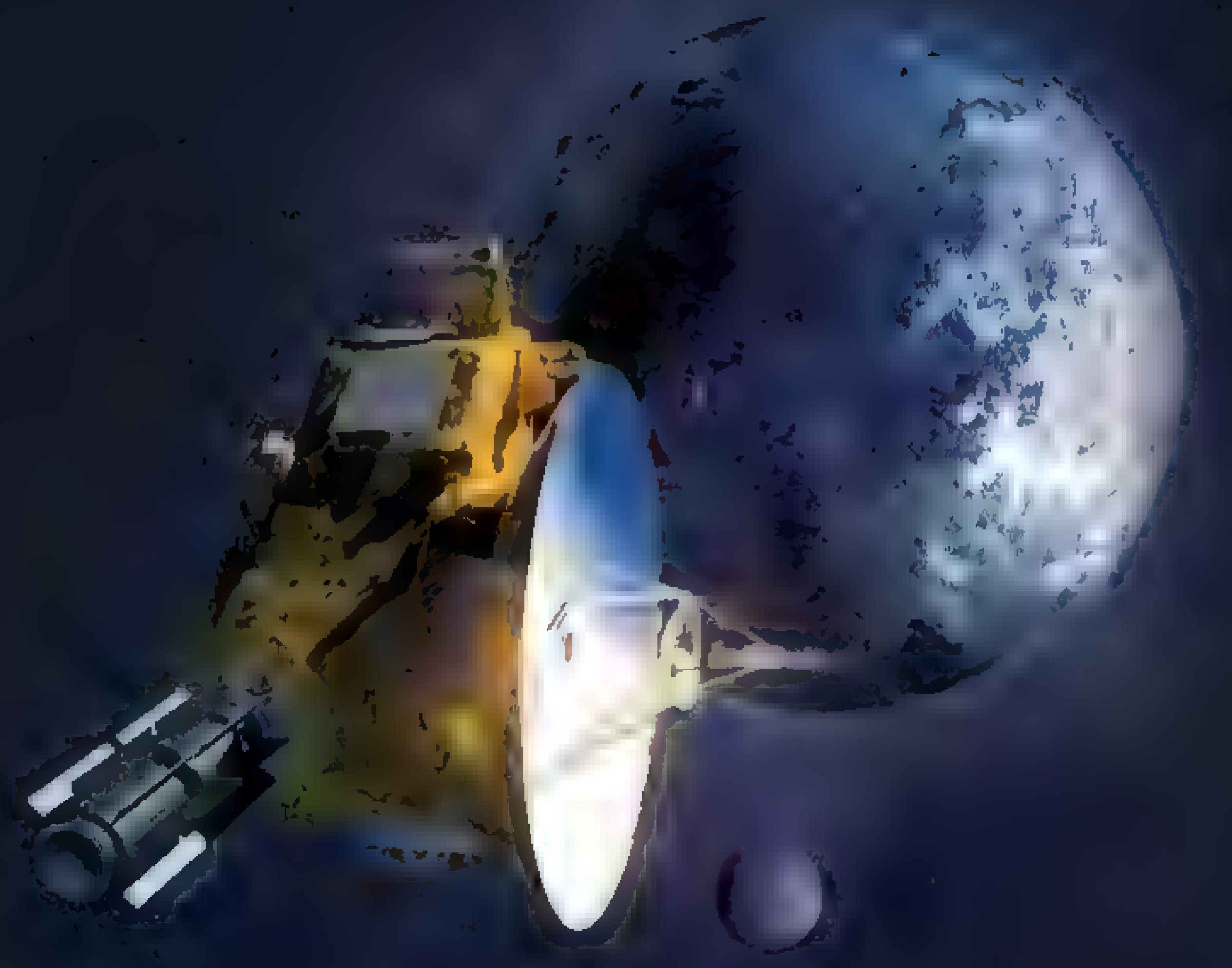


WHERE ARE ALL THE **ACTIVE SPACECRAFT** IN OUR SOLAR SYSTEM?

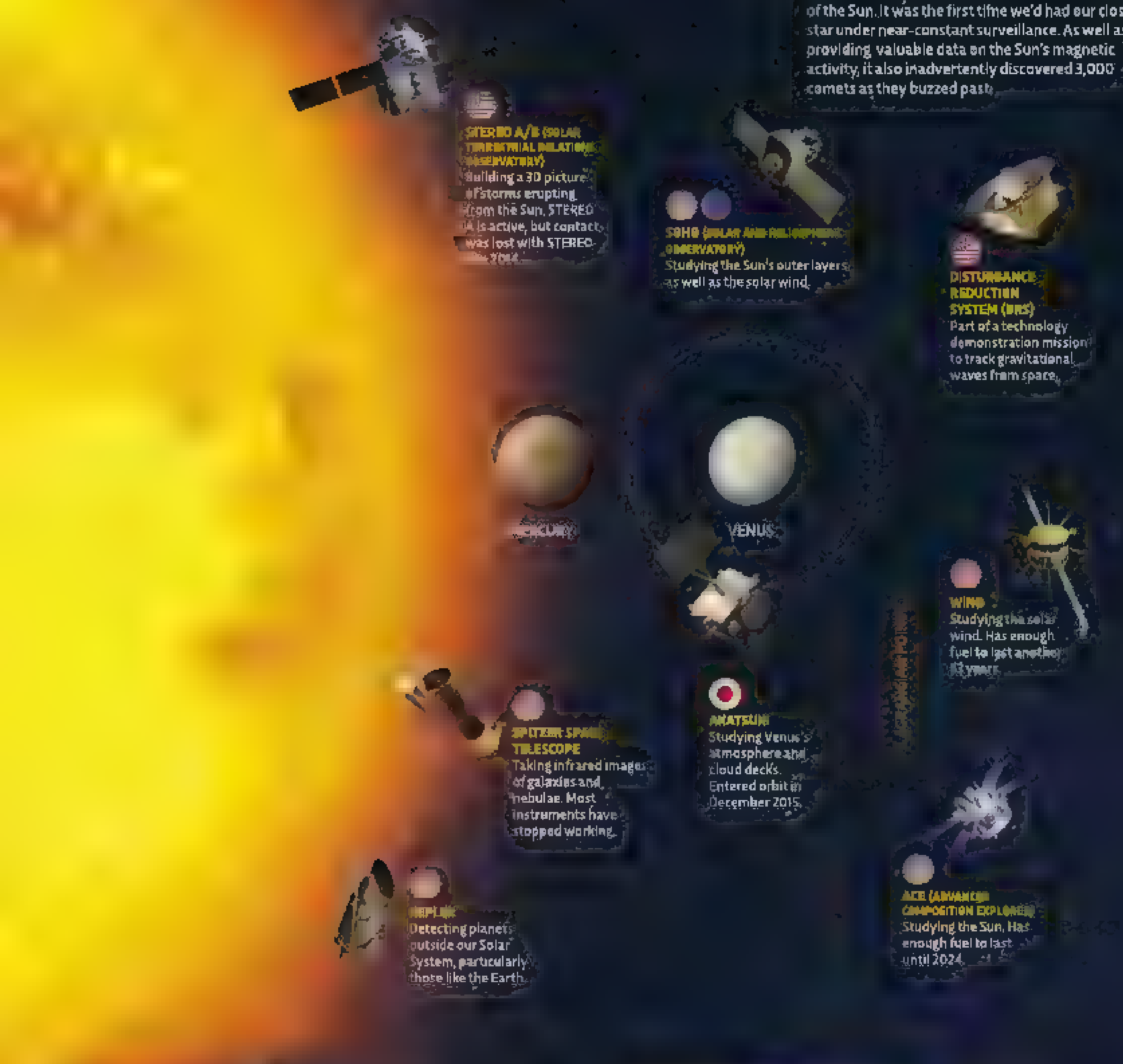
Since Sputnik 1 was launched in 1957, humans have sent thousands of spacecraft into the cosmos. There are currently around 50 active* craft in our Solar System. Here's where they are and what research they are doing

*not including miniaturised, amateur or commercial craft

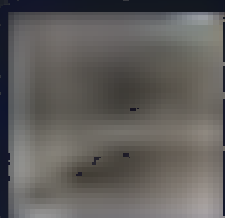
INFOGRAPHIC: TIDY DESIGNS

SOLAR AND HELIOSPHERIC OBSERVATORY

The SOHO mission revolutionised our understanding of the Sun. It was the first time we'd had our closest star under near-constant surveillance. As well as providing valuable data on the Sun's magnetic activity, it also inadvertently discovered 3,000 comets as they buzzed past.

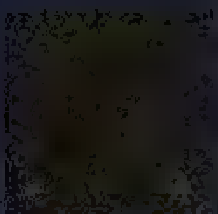


Kepler is the king of exoplanet hunters. Since its launch in 2009, this observatory has uncovered over 2,300 alien worlds by looking for small drops in the brightness of stars as planets pass in front of them. From these 'transits', astronomers can work out the size of the planet and how far it orbits from its star – crucial to work out its temperature. Kepler's haul includes Earth-sized planets with temperatures friendly to liquid water and a world with two suns.



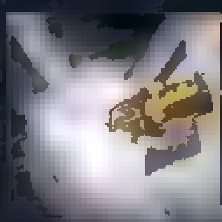
AKATSUKI

Many mysteries abound around Venus, and Akatsuki is the latest probe to take a closer look. It will search for lightning in the Venusian atmosphere, study the abundance and distribution of key gases and look at how the planet's heat is distributed in the lower atmosphere. And that heat is significant – Venus is the hottest planet, even though it isn't closest to the Sun. Letters from a public competition went along for the ride on engraved plates.



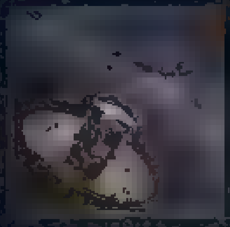
HUBBLE SPACE TELESCOPE

When the Hubble Space Telescope entered service in 1990, its images were found to be slightly blurry – traced back to a flaw in its primary mirror. A service mission in 1993 fixed the issue and, since then, the telescope has been beaming back spectacular images of the cosmos. The telescope's contribution to astronomy has been far-reaching, enabling scientists to pin down the age of the Universe, discover dark energy, and witness the birth of planets and stars.



SWIFT

Swift is designed to study gamma-ray bursts (GRBs) – intense, short-lived flashes of the most energetic form of light in the Universe. A real stalwart, it was launched in 2004 with an intended shelf life of two years, but is still operating today. So far it has seen over a thousand GRBs. When a cosmic explosion triggers the telescope, a text message is sent to the on-call astronomer so that they can coordinate any follow-up observations.



GAIA

Gaia is an astrometry telescope with the task of measuring the positions and distances of stars in our Milky Way galaxy with unprecedented precision. Twenty million stars will be analysed to a precision of one per cent. It was launched in 2013 and in April 2018 astronomers will release the hotly anticipated second batch of data to the wider astronomical community. Gaia is also studying exoplanets and distant quasars, as well as asteroids in our own Solar System.

HAYABUSA 2

Its predecessor was the first time we'd returned a sample of an asteroid to Earth. However, that mission was plagued with problems, so hopefully this time things will run more smoothly and return more material for scientists to study.

LAGRANGIAN POINT

DAWN

Dawn has gone down in history as the first probe to enter into orbit around two completely separate bodies in the same mission. Its innovative ion propulsion technology was key to getting in and out of the gravitational field of these two protoplanets. The white spots it has detected on Ceres suggest the possibility that there may be areas of water ice. Such missions are crucial precursors to any future attempts to mine asteroids for their wealth of resources.

Exploring the Moon and asteroids. Currently 100 million kilometres from Earth.

VOYAGER 1

In August 2012, it was confirmed that Voyager 1 had reached interstellar space. But it still has a long way to go before it reaches the Oort Cloud – technically still part of the Solar System. Instead, it has left the magnetic influence of the Sun, as the solar wind is lost in the winds of other nearby stars.

VOYAGER 2
Explored Jupiter, Saturn, Uranus and Neptune. Now close to interstellar space, 17.5 billion kilometres from Earth.

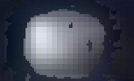
JUNO (JUPITER NEAR-POLAR ORBITER)
Arrived at Jupiter in July 2016. Now exploring the gas giant's composition, magnetism and gravity.

VOYAGER 1
Explored Jupiter and Saturn and is now in interstellar space some 21 billion kilometres from Earth.

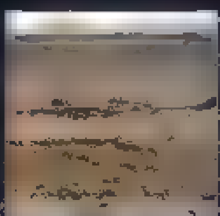
JUNO

Since arriving at Jupiter in the summer of 2016, Juno has sent back stunning high-definition images of the Solar System's largest planet. Its scientific objectives include exploring Jupiter's composition, investigating the existence of a solid core, and deciphering why the planet's Great Red Spot is shrinking. Three aluminium Lego figures were carried along for the ride – one of the Roman God Jupiter, his wife Juno and Galileo, the first astronomer to observe the planet through a telescope.

NEW HORIZONS
Explored Pluto and is now heading for the Kuiper Belt object 2014 MU69.

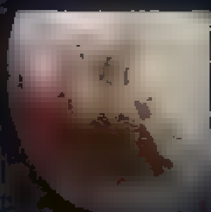


OSIRIS-REX
Will arrive at the asteroid 101955 Bennu in 2023 and return a sample to Earth.



CURIOSITY

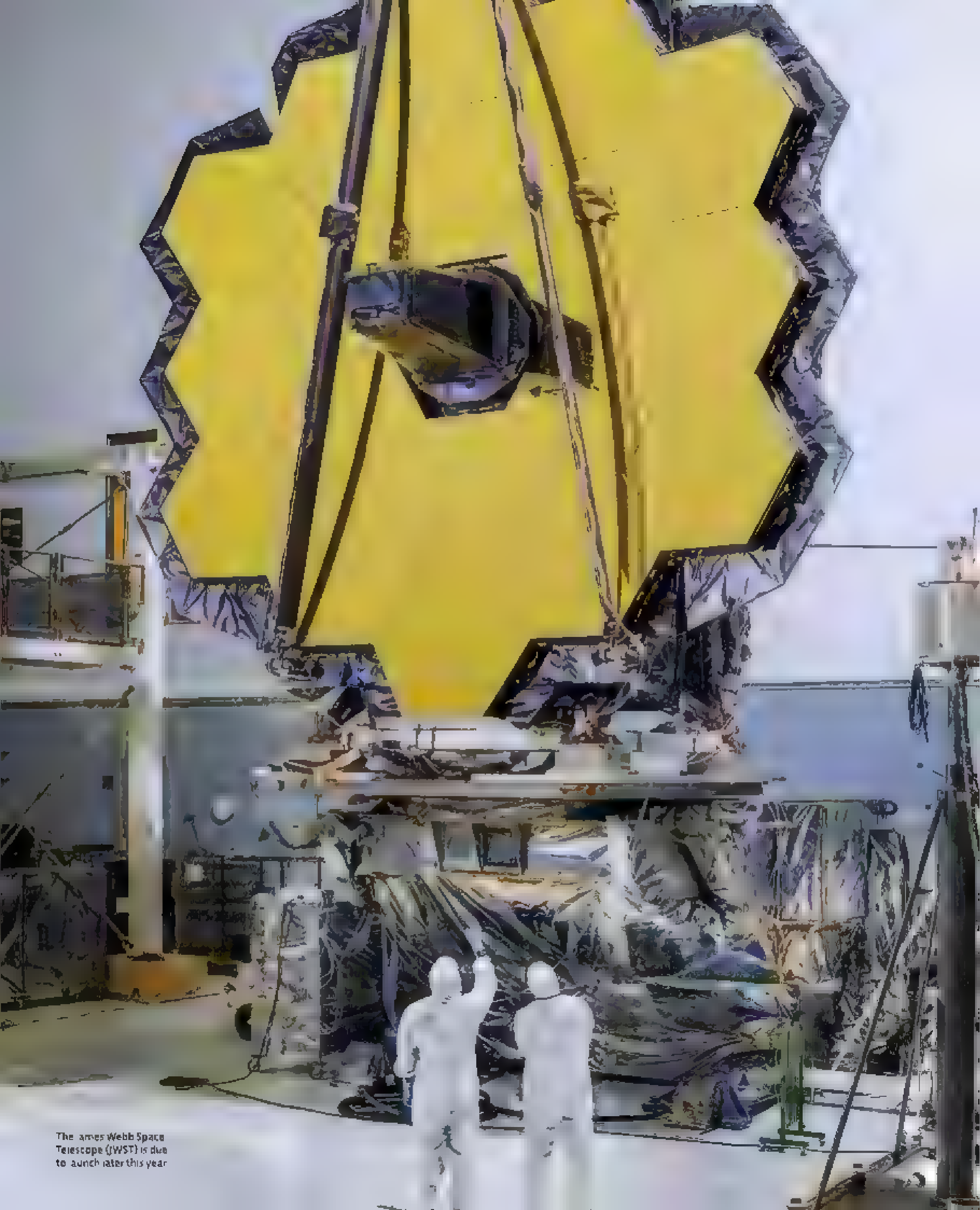
As planetary missions go, few are as daring as Curiosity. Previous Martian rovers had been lowered onto the Martian surface inside inflatable balls, which slowly deflated to leave the machine to roll out onto Mars. But Curiosity was gently lowered onto the surface via an intricate 'sky crane'. Curiosity has now experienced two full cycles of the Martian seasons. At time of writing, it was exploring Vera Rubin Ridge on the northwestern flank of lower Mount Sharp.



NEW HORIZONS

When the mission set off in early 2006, the world it was heading to was still a planet. Later that year, however, Pluto was downgraded to dwarf planet status. New Horizons finally ended its nine-year journey to the Kuiper Belt in 2015. For the first time, we had crisp, close-up images of Pluto. Scientists were left baffled by its smooth, crater-free surface, suggesting it must have some kind of geological activity that constantly re-sculpts its surface.

778 MILLION KM | 1.43 BILLION KM | 2.87 BILLION KM | 4.50 BILLION KM | 5.91 BILLION KM



The James Webb Space Telescope (JWST) is due to launch later this year

FUTURE MISSIONS

The big missions due for launch over the next few years that will explore our Solar System and beyond

WORDS: JHENI OSMAN

TESS

TARGET: **Exoplanets**
LAUNCH DATE: **March 2018**

NASA's new telescope TESS (**Transiting Exoplanet Survey Satellite**) will hunt for planets outside of our Solar System. We currently know of 3,584 exoplanets, with a new one discovered virtually every week. Unlike its predecessor the Kepler space telescope which studied some 150,000 distant stars, TESS will scan the whole sky, and is expected to find some 20,000 candidates in its first two years.

PARKER SOLAR PROBE

TARGET: **The Sun**
LAUNCH DATE: **Summer 2018**

NASA's **Parker Solar Probe** will venture closer to the Sun than any spacecraft has ever gone before – 'diving' in and out of its atmosphere, known as the corona. Its main goal is to analyse the solar wind – a continuous stream of electrified gas (plasma) launched from the Sun's atmosphere into space. Knowing more about the solar wind should help to protect the technology that we rely on day to day – such as sat-navs, telecommunications and power stations.

BEPICOLOMBO

TARGET: **Mercury**
LAUNCH DATE: **October 2018**

ESA's **BepiColombo** will study the innermost planet in our Solar System. Studying Mercury from Earth or an Earth-orbiting telescope is difficult, because it always appears close to the Sun in the sky. And it's tough to get there, basically because the planet's orbital speed is much higher than Earth's – it orbits the Sun at 48km/s on average. The spacecraft's main orbiter will be wrapped in thick thermal blankets to cope with 10 times more solar energy than in Earth orbit and intense infrared radiation. Mercury's surface is a toasty 430°C. The mission hopes to find out more about the solar wind, and investigate the planet's large iron-nickel core, its sodium-rich 'exosphere', the origin of its polar ice deposits and its mysterious magnetic field.

JWST

TARGET: **From exoplanets to deep space**
LAUNCH DATE: **October 2018**

The largest and most advanced orbital observatory ever built, NASA's **James Webb Space Telescope** (JWST) will look at the Universe in infrared, allowing us to see a side of the cosmos that has been largely hidden. It will peer through the veils of dust around stars and catch light that has been travelling since the start of the cosmos, investigating all sorts, from the smallest to the largest things in our Universe.

CHEOPS

TARGET: **Exoplanets**
LAUNCH DATE: **Late 2018**

ESA's **CHaracterising ExOPlanets Satellite** (CHEOPS) will improve our current understanding of how exoplanets form. By measuring a planet's size and mass, scientists hope to work out its composition, such as whether it is gaseous or rocky.

SOLAR ORBITER

TARGET: **The Sun and inner heliosphere**
LAUNCH DATE: **February 2019**

ESA's **Solar Orbiter** will study the Sun and the inner heliosphere – the uncharted innermost regions of our Solar System. The spacecraft will orbit the Sun at a distance of 60 solar radii, braving its fierce heat to provide unique data and images of our star.

LUCY

TARGET: **Jupiter's 'trojans'**
LAUNCH DATE: **2021**

NASA's **Lucy** spacecraft will tour Jupiter's 6,000-plus 'trojans' – asteroids which share the planet's orbit. The hope is that the mission will reveal clues as to how planets and other bodies in our Solar System formed.

PSYCHE

TARGET: **16 Psyche**
LAUNCH DATE: **2022**

NASA's **Psyche** spacecraft will journey to the unique metal asteroid 16 Psyche, which orbits the Sun between Mars and Jupiter. It's thought to be the exposed nickel-iron core of an early planet so the mission hopes to investigate the origin of planetary cores.

PLATO

TARGET: **Exoplanets**
LAUNCH DATE: **2026**

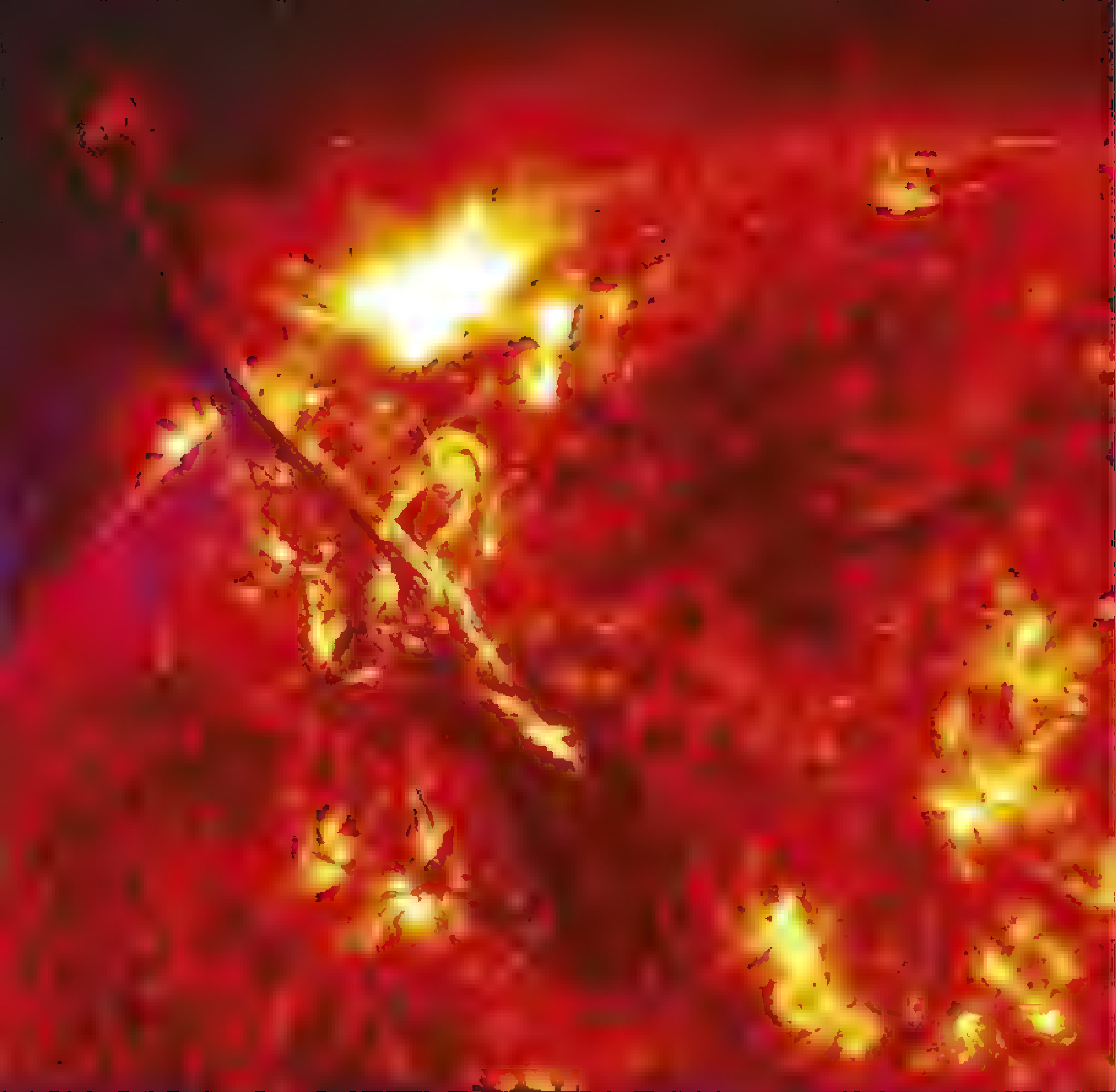
ESA's **PLAnetary Transits and Oscillations** of stars (PLATO) craft will hunt for extrasolar planetary systems, and explore the properties of terrestrial planets in the 'habitable zone' – the region around a star where the conditions could be 'just right' for life.

MISSION INTO THE SUN

We've visited Pluto and the outer reaches of the Solar System, and our rovers are trundling over the surface of Mars. Yet the Sun has remained stubbornly out of reach... until now

WORDS: STUART CLARK

This summer, NASA will launch one of its most ambitious space missions to date: the Parker Solar Probe. Travelling at a blistering 720,000km/h (450,000mph), the spacecraft will repeatedly dive closer to the Sun than any previous spacecraft in history. It will venture so close that the probe team refers to it as 'touching' the Sun. In fact, it will dive in and out of the



Sun's atmosphere, known as its corona. And it's not going to be alone up there.

In February 2019, the European Space Agency (ESA) will launch a solar mission of its own, called Solar Orbiter. This craft will not go as close to the Sun as its NASA counterpart but it will still be bathed in intense sunlight, almost 500 times that experienced by a spacecraft in Earth's orbit. Unlike Parker Solar

Travelling at a blistering 720,000km/h, the spacecraft will repeatedly dive closer to the Sun

The solar array of the Parker Solar Probe undergoing thermal tests

Probe, which spends only a short amount of time in the fierce heat as it dives in and out, Solar Orbiter will stay put for years, watching and measuring the Sun.

Both of these missions have a key goal: to find out more about the way electrified gas, known as plasma, is launched from the Sun's atmosphere out into space. This continuous stream is known as the solar wind. It carries energy and the Sun's magnetic field through space, and understanding it could solve a problem that's been mystifying scientists for decades and could be the key to safeguarding our technological society.

WHAT A WIND

When the solar wind collides with Earth, it can disrupt or even destroy electrical technology in orbit and on the ground.

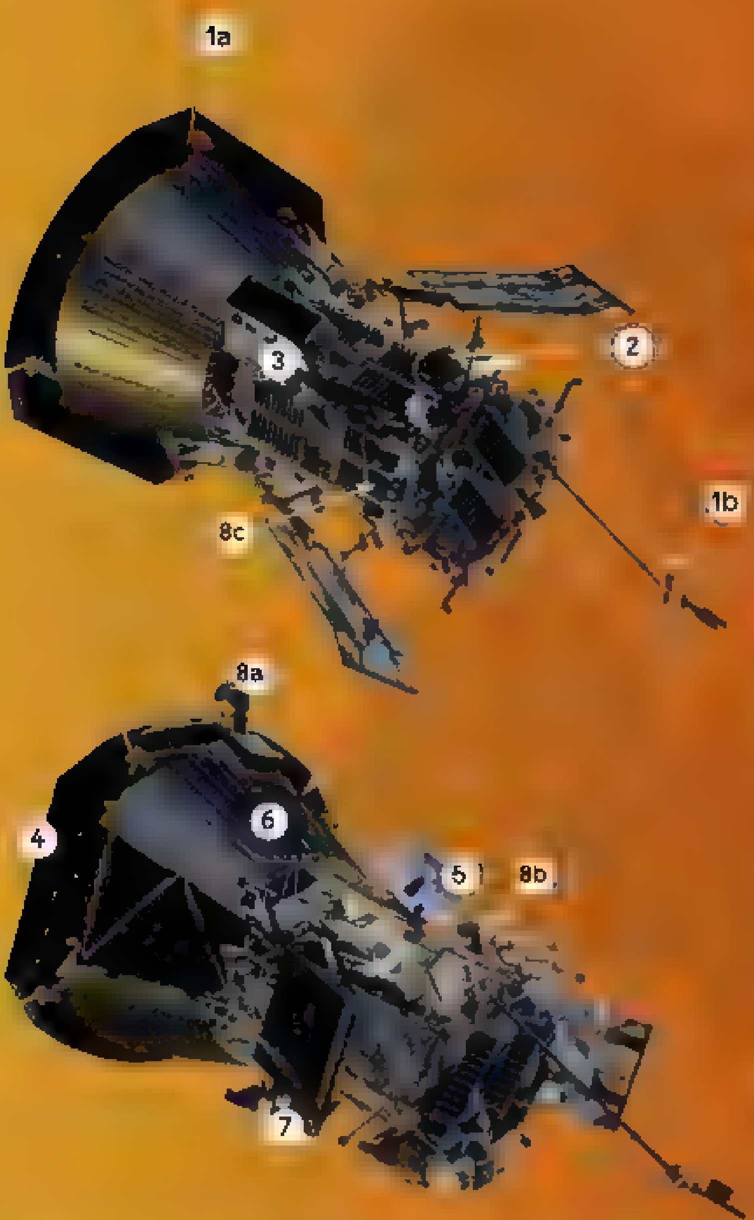
The Carrington Event, which took place in 1859, is the greatest of these so-called solar storms on record. Back then, society was more low-tech, but the global telegraph network went down and compasses spun uselessly.

Yet while solar storms of this magnitude would only happen once every couple of hundred years, smaller storms happen more frequently. Most of these cause little disruption, but all have an effect. In March 1989, for example, a small solar storm severely damaged a power transformer on the Hydro-Québec power system. It took down their power grid for more than nine hours as emergency repairs were carried out. And more recently, in 2003, a series of solar storms that took place around the Halloween period caused more than half of NASA's satellites to malfunction in some way, while aeroplanes had to be re-routed away from polar latitudes because of the large amounts of radiation associated with the intense aurora.

One recent study by the US National Academy of Sciences found that without advance warning, a huge solar flare, carried by the solar wind, could cause $2tr worth of damage in the US alone, and it would not be quick to fix. The report found that such an enormous solar flare could cause so much damage to power stations that the US eastern seaboard could be left without power for a year. Europe is similarly vulnerable.

Without advance warning, a huge solar flare, carried by the solar wind, could cause $2tr worth of damage in the US alone

While studying the Sun has never been more timely, the desire to do so stretches back before the space age to the 19th Century, when a solar mystery was uncovered. On 7 August 1869, astronomers gathered across Russia and North America to observe a total solar eclipse. In those fleeting minutes of darkness, the scientists got to see something not visible at any other time: the ghostly veils of the solar corona, the Sun's outer atmosphere. It was an object of fascination for the astronomers of the day. Two of the astronomers, Charles Augustus Young and William Harkness, were using spectroscopes to split the coronal light into its constituent wavelengths. They knew that the various chemical elements gave out light at



PARKER SOLAR PROBE

FIELDS EXPERIMENT
Makes direct measurements of electric and magnetic fields and waves in the solar wind and of density fluctuations and radio emissions

INTEGRATED SCIENCE INVESTIGATION OF THE SUN (ISIS)
Observes highly accelerated electrons, protons and heavier particles, and correlates them with solar wind and coronal structures

WIDE-FIELD IMAGER FOR SOLAR PROBE (WISPR)
Provides images of the solar wind, shocks and other plasma structures as they approach and pass the spacecraft

THERMAL PROTECTION SYSTEM (TPS)
An 11.43cm-thick carbon-composite shield that will withstand temperatures outside the spacecraft that reach nearly 1,377°C

6 HIGH GAIN ANTENNA
Used to communicate with Earth. The downlink data rate when close to the Sun will be around 167kb/s. Not much compared to modern broadband speeds

SOLAR ARRAY COOLING SYSTEM
Operating in 475 times the solar intensity experienced in Earth orbit, the solar arrays are cooled by a 4m² radiator that sheds waste heat into space

7 SOLAR ARRAYS
Although just 1.55m² in area, the solar arrays generate 388W of electrical power at closest approach to the Sun

SOLAR WIND ELECTRONS ALPHAS AND PROTONS (SWEAP) INVESTIGATION
Counts the most abundant particles in the solar wind and measures their properties such as velocity, density and temperature

specific wavelengths, and by measuring these 'spectral lines' they would be able to establish the chemical components of the corona. Working independently, they both discovered a green spectral line with a wavelength of 530.3nm. It caused great excitement at the time because there was no known chemical related to this wavelength, so the astronomers thought they had discovered a new element. They named it coronium.

It turned out that Young and Harkness were wrong, yet it wasn't until the 1930s that scientists understood why. Astrophysicists Walter Grotrian and Bengt Edlén conducted laboratory experiments and found that iron could give out that green light, but only if it were heated to an extraordinarily hot 3,000,000°C, turning it into plasma. With this realisation the real mystery was born. What exactly is heating the Sun's corona to 3,000,000°C? The magnitude of the problem is enormous because the surface of the Sun is a mere (astronomically speaking) 6,000°C. "It defies the laws of physics and nature. It's like water flowing uphill. You move away from a heat source and it should get cooler not hotter," says Nicola Fox, mission project scientist at the Johns Hopkins University Applied Physics Laboratory. "What happens in this region that suddenly accelerates all of this coronal material to temperatures ●

The Sun at the moment of an eruption

The solar wind bathes the planets, and when it collides with the Earth, it sparks stunning auroras

exceeding 3,000,000°C? It is mystery number one," says Fox.

And if that wasn't a big enough conundrum, there is a second, related mystery. The gas breaks away from the Sun just where the temperature peaks. "If you think of the Sun as a giant gravitating star, it is going to hang onto its material. And yet the plasma is able to break away and move out and bathe all of the planets," says Fox.

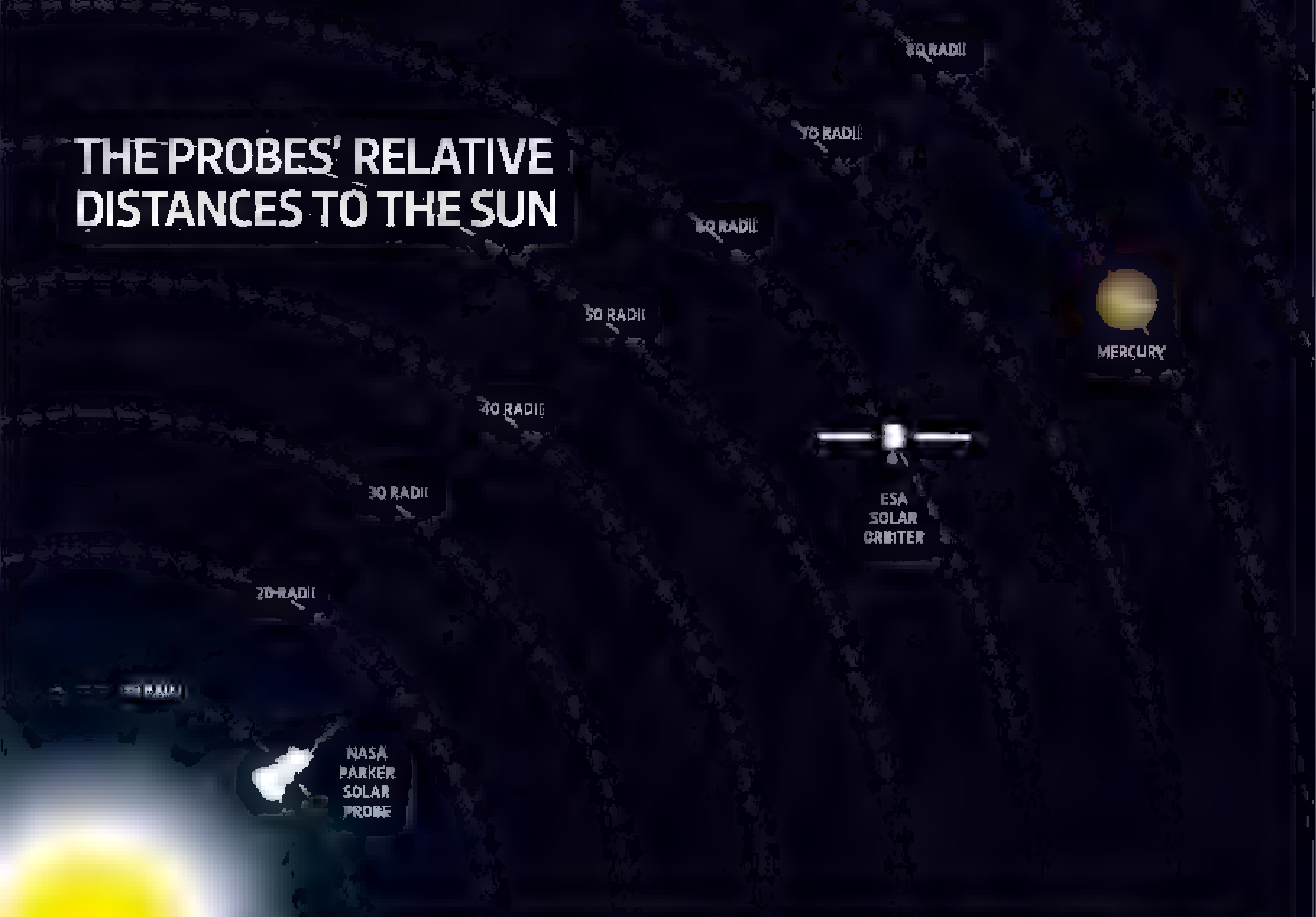
This solar wind that Fox refers to is made mostly of hydrogen and helium. The iron that betrayed the corona's great temperature actually makes up just a tiny fraction of its composition. The solar wind carries with it the Sun's magnetic field and streams out into space at about 1,600,000km/h (1,000,000mph). It bathes the planets, and when it collides with the Earth, it sparks the stunning auroras that shine in the polar skies.

STAY COOL

Astronomers say that the acceleration of the solar wind occurs at about 10 solar radii (one solar radius is equal to the radius of the Sun). "That's where Parker Solar Probe is going, it's a scientifically important region of space," says Imperial College London's Prof Tim Horbury, who is a co-investigator on Parker Solar Probe's FIELDS instrument.

Through its series of extraordinarily close encounters with the Sun, Parker Solar Probe will repeatedly explore this key region. It will survive its plunge thanks to an innovative thermal protection system (TPS). This heat shield is made of two plates separated by a layer of carbon foam. The layer that faces the Sun is white and reflective. The foam itself

THE PROBES' RELATIVE DISTANCES TO THE SUN



Parker Solar Probe will 'dive' as close as 10 solar radii to the Sun, whereas Solar Orbiter will remain a constant 60 radii away

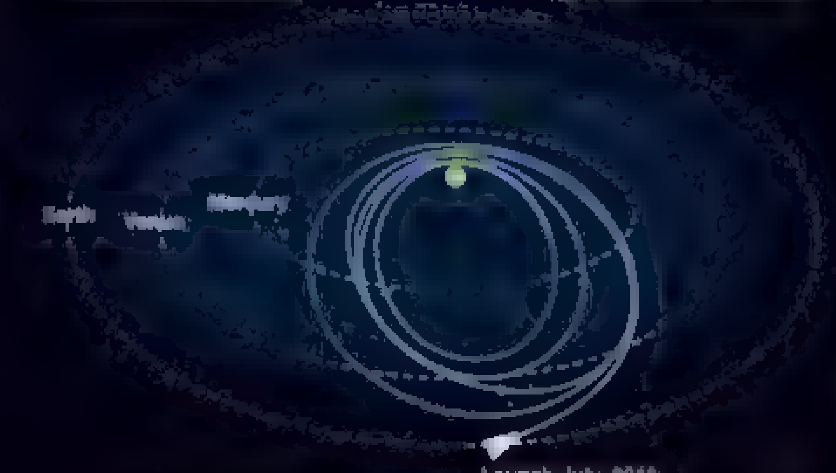
is diffuse and light, and is composed of 97 per cent air. It was developed and manufactured especially for the spacecraft and is one of the key technologies that has enabled the mission to take place. It is just over 11cm thick, and will be heated to around 1,377°C during its close solar passes. On the other side of the TPS, where the spacecraft is located, the design will almost completely dissipate the heat, reducing it to a comfortable room temperature of around 21°C.

Solar Orbiter's heat shield takes a different approach because it has to withstand lower but constant heating. Its maximum temperature is likely to be around 520°C, but it is not going to head out to the orbit of Venus to cool down, like the Parker Solar Probe. Solar Orbiter's heatshield is pitch black rather than white and reflective, as this means it will absorb heat and radiate it back out into space. It is made from titanium covered with a protective skin called SolarBlack, which is derived from a charcoal-based pigment made of burnt animal bones. This pigment is a type of black calcium phosphate and is widely used for fertiliser and metal alloy production, and for filtering heavy metals out of water. This skin keeps the European space probe safe so that it can operate continuously at a distance of 60 solar radii. Although this is six times further away than Parker Solar Probe's closest approach, there is a particular reason for choosing this distance. "It goes as close as you can go and still use telescopes to look at the Sun," explains Horbury. Parker Solar Probe's only telescope looks to the side to take images of the solar wind rushing by.

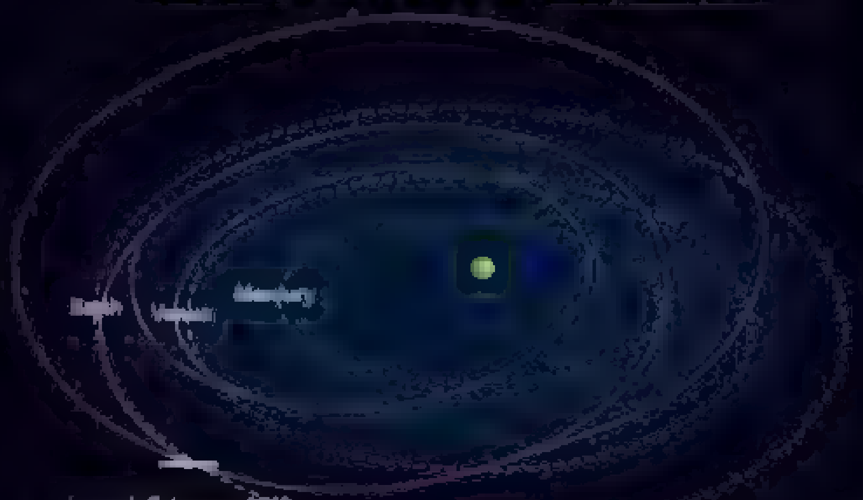
Solar Orbiter's telescopes will study the Sun's surface with a variety of instruments over a wide range of different wavelengths so that astronomers can determine the surface gas's densities, temperatures and the magnetic field. It then contains a second suite of instruments that measure the same properties for the solar wind as it passes the spacecraft. Parker Solar Probe is designed to fly through the exact region of the Sun's atmosphere where it breaks its connection

> **They should help us to safeguard the tech we rely on every day – from sat-navs to telecommunications to power stations**

PARKER SOLAR PROBE'S LAUNCH PATH



SOLAR ORBITER'S LAUNCH PATH



to the solar surface and becomes the solar wind. So by sharing their data the mission scientists can make the connection between events on the solar surface, the launching of the solar wind, and the downstream conditions. This is the stuff of dreams for the people involved in understanding space weather.

"Solar Orbiter is about making the connection between what happens on the Sun and what happens in the solar wind," says Horbury.

EARLY WARNING

Solar storms throughout history have shown how the interaction of the solar wind with Earth's magnetic field can severely damage important technology. So, while these missions to the Sun are likely to reveal all sorts of interesting data and maybe even new theories about our star, more crucially, they should help us to safeguard the tech we rely on every day – from sat-navs to telecommunications to power stations.

Currently, we get only 30 to 60 minutes warning from a NASA spacecraft called ACE (Advanced Composition Explorer). Once these two missions have performed their work, the hope is that this warning time will rise to a day or two. That's because solar storms are sparked by flares on the Sun that trigger a sudden ejection of material from the corona into the solar wind. It takes a day or two for this eruption to cross space, so knowing the way in which the solar wind is launched is critical if we are going to calculate the severity of any incoming solar storms. It could also give us more time to prepare and protect any important electrics.

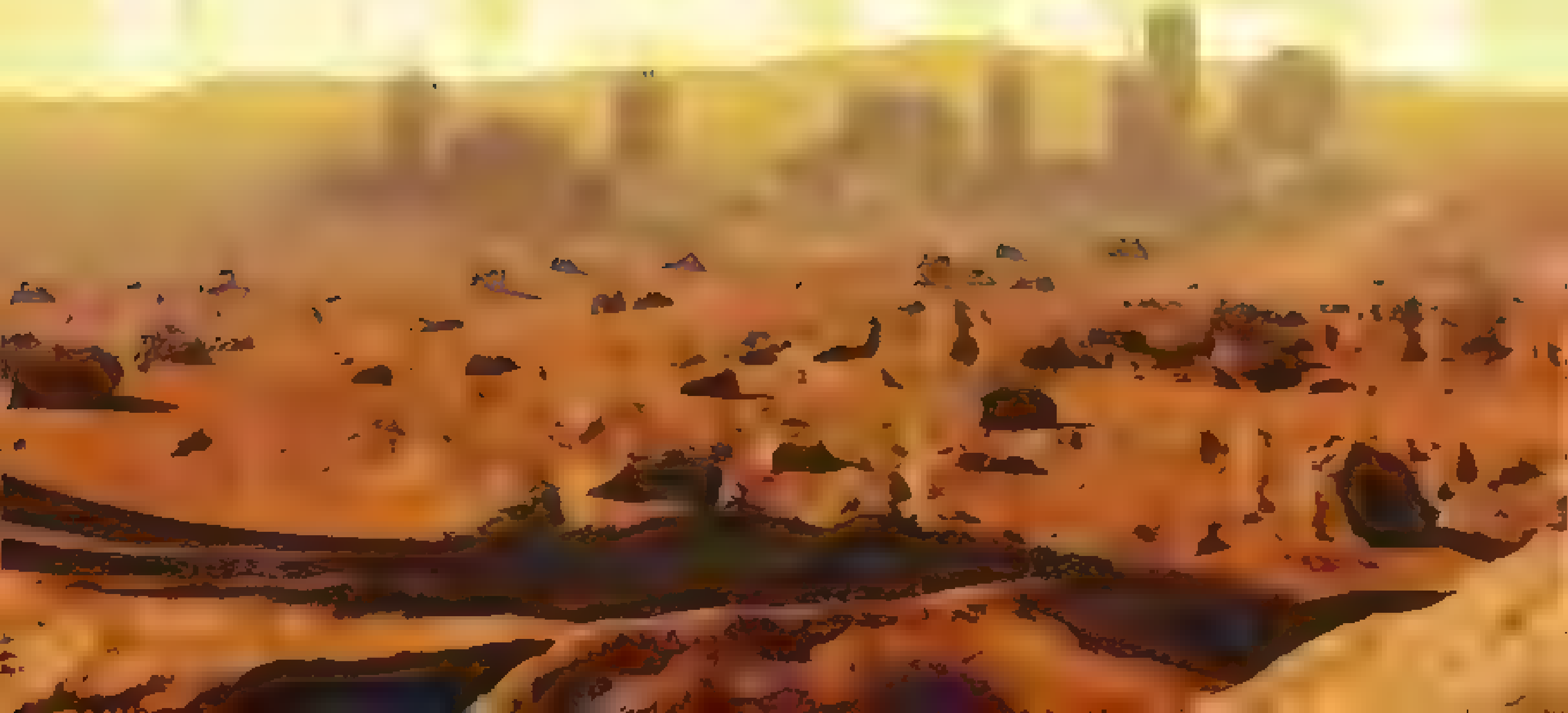
"The data we are supplying will be used to make transformational improvements to the models. A few years from now when we see a big event, the model is going to accurately tell us what is coming to the Earth," says Fox. "It is extremely fortuitous that we have the two missions going up in a similar time frame. They are so synergetic, that I couldn't be more excited that they will be up together. It's perfect." ●

Dr Stuart Clark is an astronomy writer with a PhD in astrophysics. His latest book is *The Unknown Universe*


ONE W

AY TO MARS

What if something goes



SELECTION

Prof Suzanne Bell

Prof Bell works on NASA's Human Research Program, looking at the qualities needed in astronauts taking part in a long term space mission such as colonising Mars

WHAT KIND OF PERSON WOULD YOU PICK FOR A MISSION TO MARS?

It goes without saying that working and living in such an extreme environment will require capable individuals who are compatible with each other. They'll be intelligent, fit, adaptable and stable, with great coping and teamwork skills. But there are some other considerations that are more nuanced.

It's no surprise that introverts do better in isolated and confined spaces: the isolation and the social monotony of space require a certain level of introversion. At the same time, there is a level of social warmth associated with extroverts that would be beneficial, as team members rely on one another for social support. So how can this paradox be managed? Well, in this case you can have the best of both worlds – ambiverted individuals have qualities of both introversion and extroversion.

I'd also look for team members who are high in self monitoring – that's the ability to show concern for, and appropriately modify, your behaviour in a social situation. Have you ever been in a meeting, wanted to say something, and then thought to yourself, "It's not very important that I say this right now"? If so, you were self monitoring. This will help keep conflicts manageable and the team effectively negotiate the status and power issues that are likely to come up in the new settlement.

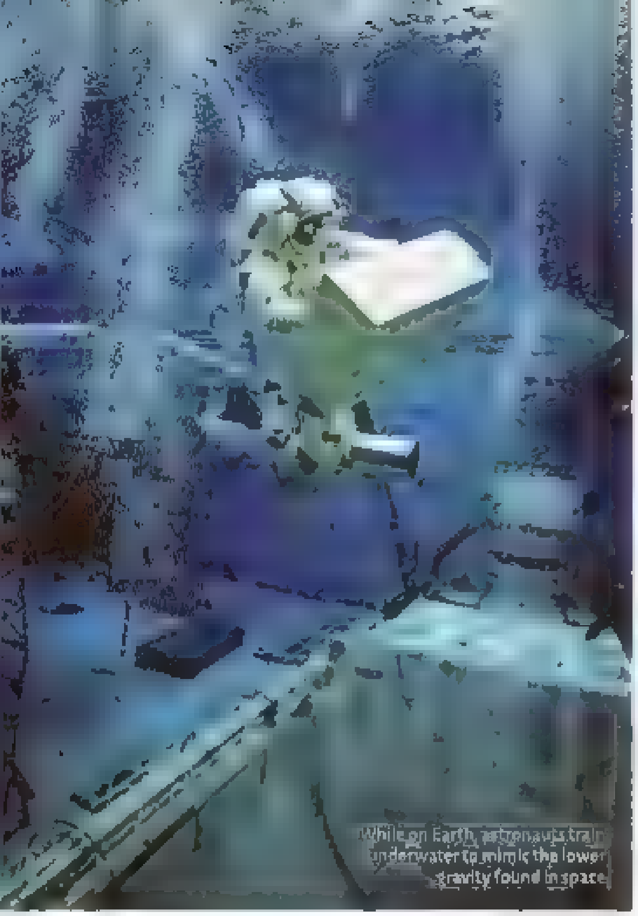
Of course, going to Mars is a risk, but you won't want someone who is too much of a risk taker – some people take risks because they haven't appropriately weighed up the consequences. Living and working in a hostile environment means that one small mistake could have major consequences: it could even mean the death of the team. So the right person will be able to be careful and responsible in their actions, yet still have a great sense of adventure.

Ensuring team members have shared values is also critical to their compatibility. Personal values are ordered in terms of relative importance, and they drive behaviour. The team that is sent is likely to be diverse in a number of areas. Shared values are critical for bridging these differences. For example, the team may have a mix of scientists and non scientists (such as the pilot). When the team is faced with a situation that presents competing priorities (for instance, whether to lose data or preserve equipment), the team will more easily agree on a course of action if they have shared values.

> "Even the most carefully selected, emotionally stable team members will struggle with the extreme isolation at some point"

HOW WOULD YOU PREPARE SOMEONE FOR A ONE-WAY MISSION TO MARS?

Preparation will involve extensive training, and ensuring that the team has accepted agreed procedures and standards. Training will need to include obvious knowledge and skills (how to land the spacecraft) as well as everyday activities that aren't quite so simple in space (how to go to the bathroom in zero gravity). Teams also will need to be trained in several areas critical to the team's self sufficiency: learning how to learn, coping skills and teamwork skills. The needs of the settlement will likely change over time and unanticipated events will occur. It's critical to have not only intelligent team



While on Earth, astronauts train underwater to mimic the lower gravity found in space

NASA

members but also those who can evolve – for example, those who can self-regulate their learning. Self-regulation is thinking about thinking, using strategic action to learn. There's no human with the perfect skillset for life on Mars – some kind of pilot-cum-farmer-cum-doctor. But if we can teach a candidate to teach themselves, to adapt, to evolve, then they'll have the toolset they need to survive. For example, an astronaut who can identify precisely what part of the landing procedure they're getting wrong, and the training they need to correct the problem will be more valuable on a long-term mission.

Even the most carefully selected, emotionally stable team members are likely to struggle with the extreme isolation at some point. The team will need to be trained in coping skills – how to identify and respond to difficulties in coping and strategies for providing support.

Although training will be key to team preparation, many issues will be best resolved with agreed-upon standards. Individuals from different backgrounds may have different views on living standards, personal hygiene or even the treatment of women. Making sure everyone is on the same page regarding these issues can be used to keep conflicts at a manageable level.

SPACECRAFT

Prof Mason Peck

How will we get to Mars? Prof Peck, former Chief Technologist at NASA, outlines Mars One's plans for making the challenging journey to the Red Planet

HOW WOULD YOU SEND A CREW TO MARS?

The four person crew will travel to the Red Planet in a transit vehicle – a small space station that will be assembled in low Earth orbit before the crew arrives. In-orbit assembly allows us to build large space systems, like the International Space Station (ISS), that we're unable to launch intact from Earth, for technical or financial reasons.

Once the crew is onboard, the transit vehicle will fire its engines and begin its journey to Mars. This will be the astronauts' home for seven months, and they'll eat, sleep and train in the vehicle's habitat module. Then, when they're near Mars, they'll enter a separate lander module, a bit like the Apollo landers.

The Mars One crew will be launched into space on a SpaceX Falcon 9 rocket

The one way journey needs less than half the supplies of a round trip. They'll have enough water and oxygen onboard to last them for the whole journey, as well as plants to grow more food should they run out. The transit vehicle will also have an environmental control and life support system (ECLSS) to control air pressure, detect fires, monitor oxygen levels and manage water and waste, but this won't need the longevity of existing ECLSSs, like on the ISS. This reduces the hardware costs involved.

A key feature of Mars One is its use of existing technologies, in contrast to the usual practice of creating a custom built spacecraft for every mission. So no new launch vehicle will need to be designed for Mars One. Instead, the four person crew will be carried to the orbiting transit vehicle by a pre-existing system, such as SpaceX's Falcon Heavy. It'll be a similar approach to the way astronauts travel to the ISS today.

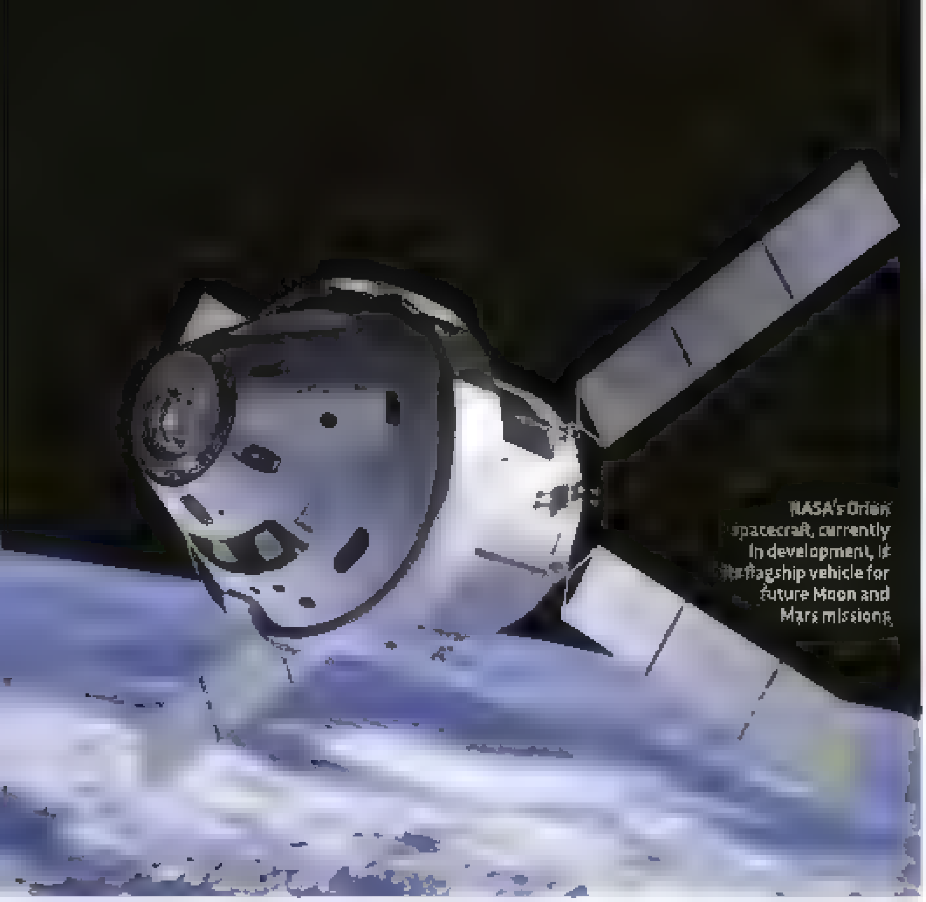
We'll continue sending four person crews to Mars at every launch opportunity – roughly every 26 months, when Mars and Earth align in a way that minimises the propellant needed for the trip. As more colonists arrive, the first Martian settlement will begin to take shape.

HOW WILL YOU LAND ON MARS?

Landing won't be easy. NASA's analysis predicts that a successful six-person mission would need to land 40,000kg on the Martian surface. Mars One's mass will be lower because of its smaller crew, but still, the largest payload delivered to date is just 1,000kg (the Mars Science Lab mission, which landed the Curiosity rover in 2012). This leaves quite a few challenges ahead for Mars One.

Fortunately, NASA's previous successes and investment in future technologies should provide us with a solution. One possibility is aerocapture – slowing the vehicle down by sending it through the Martian atmosphere. This would create a drag force, reducing the craft's orbital energy. Secondly, inflatable aerodynamic decelerators might be used. Currently in development, these expand to create a large, lightweight, heat resistant body that further slows the vehicle.

Some rocket companies are also looking into landing vehicles through retropropulsion – the Buck Rogers technique of firing rocket engines in front of you to slow yourself down. SpaceX and NASA have agreed to share data on supersonic retropropulsion gleaned from a launch of SpaceX's Falcon 9 in September 2014. This technology can be tested here on



NASA's Orion spacecraft, currently in development, is the flagship vehicle for future Moon and Mars missions

Earth, replicating Mars's atmospheric conditions by performing experiments at just the right altitude. It'll be a combination of these technologies that will allow the Mars One lander to reach the surface.

WILL YOU NEED OTHER SUPPORT MISSIONS?

Absolutely. One strength of the Mars One concept is its focus on infrastructure – it's not just a one-shot, single-purpose mission. In 2018, six years before the first crew's departure, two communications satellites will be launched – one around the Sun and one around Mars – allowing constant communication between Mars and Earth. Laser communications, a new NASA-developed technology, will increase data frequency transmissions. A demo mission around this time might also test some of the landing procedures. From 2020 through to 2024, there'll be a further series of preliminary missions to carry out some prospecting around the landing site, set up the area for human habitats and collect resources. These initial preparations will mean the first colonists have somewhere to rest and recuperate when they do finally arrive.

> "We'll continue sending four-person crews to Mars at every launch opportunity – roughly every 26 months"

ONBOARD ORION

The NASA spacecraft to take humans to Mars and beyond

Orion has been designed to take humans farther than they've ever gone before. The plan is for it to serve as an exploration vehicle, carrying crew, providing emergency abort capability, sustaining crew during space travel, and providing safe re-entry from deep-space return velocities.

The plan is to launch Orion aboard the new Space Launch System, sending it into orbit around the Moon. This mission – Exploration Mission 1 – will be used to test the guidance and navigation systems, as well as the radiation protection equipment.

By 2023 the first manned mission will be launched, called Exploration Mission 2. This mission is currently proposed to send astronauts to a captured asteroid, so they can collect samples and bring them home.

Before any humans fly onboard Orion, one hugely important part of the system will be thoroughly tested. The Launch Abort System (LAS) fits around the crew module, with a spike housing three rocket motors. If the main rocket should fail, the LAS's rockets would fire within milliseconds to pull the crew module out of harm's way before deploying parachutes for a safe landing.

But many challenges lie ahead before the final goal of sending astronauts to Mars. At present Orion is designed to only take four astronauts for missions lasting up to 21 days. This is because there isn't enough space to store water and supplies for longer missions. An eventual mission to Mars would rely on various other components, such as a habitat module.

But the need for humans to undertake such missions is something that NASA is convinced is necessary. Exploration Flight Test 1 was just the start of a long journey for NASA, but it is one that could ultimately mark the start of a new wave of human space exploration of our Solar System and will inspire a new generation of scientists and engineers.

Orion undergoing final assembly at the Kennedy Space Center. Technicians ensured that no foreign objects contaminated the spacecraft

NASA, SPACEX

WELLBEING

Dr Kevin Fong

Dr Fong has worked with NASA and is author of *Extremes: Life, Death And The Limits Of The Human Body*. He explains how the body would cope on Mars

WHAT SHOULD A DOCTOR ON A TRIP TO MARS BE MOST WORRIED ABOUT?

A Mars mission crew doctor will have their work cut out. Prevention is always better than cure, so keeping the crew healthy by making sure they eat the right diet, stick to an exercise programme and generally take care of themselves would be important. But a crew physician would be responsible for providing healthcare should any medical emergency arise. With space and power at a premium, and the physician having to be everything from general practitioner and casualty doctor to anaesthetist and surgeon, that would be a tall order. And there's plenty up there in the way of threats: the effects of weightlessness, the risk of decompression illness during space walks, the intense radiation outside the protection of Earth's magnetic field, and micrometeoroids.

The biggest threat to life, though, is not disease or even traumatic injury. Astronaut crews are screened to make sure they're in peak condition, and the spacecraft itself and all activities that take place within it are designed to expose the crew to the lowest possible risk of injury. Day-to-day life would be far safer than in the average house: you can't fall down a flight of stairs, it's hard to start fires and it's nearly impossible to electrocute yourself. Instead, what would most worry a doctor would be being part of a crew that's hurtling through space, powered by rockets with the explosive potential of a small nuclear missile. It's not the medicine you need to worry about, it's the rocket science. We've never lost part of the crew on a space mission: either the engineering works and everybody lives, or it doesn't and everyone dies.

WHAT WOULD HAPPEN TO THE HUMAN BODY AFTER A YEAR ON MARS?

Mars doesn't support life any better than the empty space that the crew would have crossed to reach it. It is smaller than Earth and further from the Sun, with a thin atmosphere composed almost entirely of carbon dioxide. So when crews arrive there, they will be completely dependent upon a suite of life support systems, and forced to live in habitats that are suitably shielded from radiation. But the aspect of Martian life that will shape physiology more than any other is the reduced gravity.

Astronauts living on Mars will experience roughly one-third of the gravity that they would on Earth. We already know, from more than 50 years of human space flight, that weightlessness has effects on the human body. Bone and muscles waste rapidly and the heart, which is itself a muscle, deconditions. But other systems are also affected. Hand-eye coordination becomes impaired, the immune system becomes suppressed and astronauts can become anaemic. Prolonged weightlessness can take athletes and turn them into couch potatoes very quickly.

What we don't know for sure is how severe these effects will be on Mars. On the Red Planet there is at least some gravity but it's unclear if

> "For now, a combination of drugs, controlled diet and exercise regimes will be what crews rely upon to ward off the deconditioning effects of living with reduced gravity"

Exactly how the low gravity conditions on Mars will affect long-term settlers remains so far unknown

Diego Urbina training as part of the Mars500 mission, which simulated a manned Mars voyage

it's enough to protect the astronauts' biology. Over the years, we've studied hundreds of people who've spent time floating weightlessly but only 12 people who've ever experienced reduced gravity on the surface of another world: the Apollo crews who landed on the Moon. And that's left us without enough information to know for sure how severe the problem of life on Mars, at one-third of Earth's gravity, will be.

For now, a combination of drugs, controlled diet and strict exercise regimes will be what crews rely upon to ward off the effects of living on a world with reduced gravity. Some authorities have proposed using short arm centrifuges to provide a short burst of artificial gravity. But what's clear is that the exploration of Mars will also prove to be an exploration of the limits of the human body.

COLONISATION

Prof Charles Cockell

Prof Cockell is director of the UK Centre for Astrobiology. His lab investigates life in extreme environments. He explains what life will be like [illegible]

WHAT WILL THE FIRST FEW DAYS BE LIKE?

The new settlers' first priority will be putting in place the basic essentials for survival, and ensuring backup systems function. They'll need to ensure that all oxygen production and recycling equipment is working, and if they're topping up their oxygen from water gathered from the atmosphere (by breaking it down using electrolysis), they'll need to check that the extractor fans collecting atmospheric water are up and running.

In the first weeks, the food the colonists will eat will not be home-grown. They'll be eating dried and preserved rations in boxes. However, they may spend the first two weeks setting up a simple greenhouse so that they can begin to grow food as soon as possible.

A crucial matter for survival is energy. Whether they're using nuclear or solar energy, they'll need to set up the apparatus, link it to the base and make sure that the power supply is stable and reliable. They may also set up chemical apparatus to make useful things like fuel. Carbon dioxide in the atmosphere, for instance, can be reacted over a catalyst with hydrogen (itself released from water gathered from permafrost or the atmosphere) to make methane fuel to power their robotic rover.

The Sun produces infrequent, but intense, particle streams that can cause severe radiation damage. So the settlers will need to ensure that radiation shielding is in place – for example a layer of Martian rock or water in the walls of their habitat would do the job – and that they have a more resistant shelter to escape to during periods of intense radiation.

Most of these procedures will have been tested before they land, so in principle it should just be a matter of plugging in the equipment. But they will still need to check and cross-check all of these systems in a potentially lethal environment. The first few days will be a Lego-like frenzy of putting together the first Martian base.

WHAT WILL THE COLONISTS NEED TO THINK ABOUT BEYOND SIMPLE DAY-TO-DAY SURVIVAL?

Beyond the science and planning there is the human story. These explorers will inhabit a deadly environment, trapped in a tiny space with their fellow colonists. Their challenges will come not just from the outside (the Martian environment) but also from the inside – the human challenge. Professionalism and good behaviour will get them a long way as they learn to work together and carry out their mission,

The settlers' living quarters will include a greenhouse for growing fresh vegetables and a surprisingly comfortable area for rest and relaxation

but other things will help. For instance, they'll have small spaces in the station where they can spend time on their own, write messages to loved ones on Earth, paint or read.

We know from the accounts of those who've lived on space stations that growing crops and tending to other creatures helps a great deal by giving people psychological reprieve from the extreme environment.

As a small group, direct participatory democracy will probably work, but as numbers grow they may need some formal constitution by which to govern themselves. It'll be the first extraterrestrial government.

The Mars One crew members will need to be capable of living in close proximity to their fellow colonists in a deadly environment

"The Sun produces intense particle streams that cause severe radiation damage. So settlers will need radiation shielding"

MARS ONE TIMELINE

If all goes according to plan...

2018
Crews currently in training replaced by new crews from regular astronaut selection programs.

2022
An unmanned demo mission is launched to test the landing procedures on Mars. Two communications satellites are also sent into orbit, providing constant communication.

2024
Dedicated Mars synchronous communications satellite sent to Mars.

2026
A robotic rover is launched. Once it has arrived on Mars, the rover drives around to find the best location for a settlement. It then prepares the surface for the arrival of the next missions.

2029
The first cargo missions are launched. These carry essential items such as food and solar panels, as well as inflatable living units and equipment to generate water, energy and breathable air.

2031
The first Mars One crew begins the journey from Earth. They are the first humans to embark on a mission to Mars.

UNKNOWN UNIVERSE

[illegible] pened up new frontiers in cosmology. Find out about [illegible]

EXOPLANETS

Planets lurking in solar systems many light-years away could help us learn more about the Universe and life itself

Exoplanets are planets that orbit stars other than our Sun. We currently know of 3,584, and the number rises every week.

About one-third of nearby stars have planets, and a further third have dust disks from which planets congeal. Consequently, in our Milky Way, there are almost certainly more planets than stars – and there are several hundred billion of those.

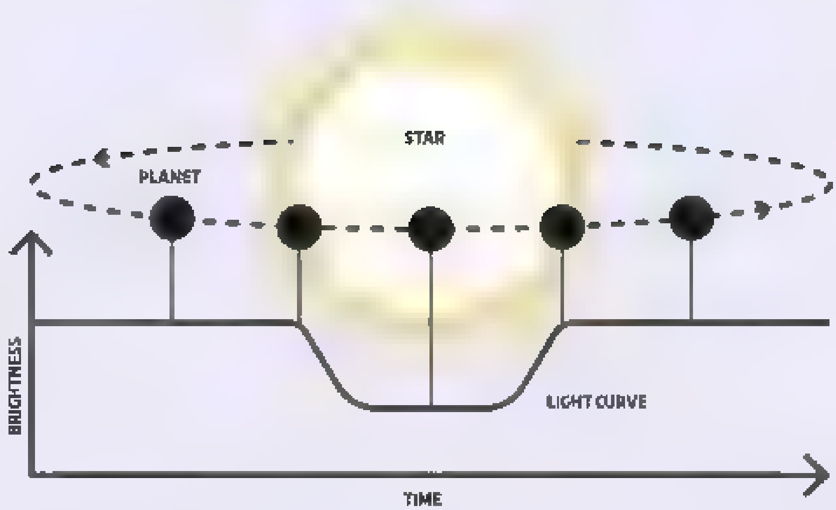
Before the discovery of the first extrasolar planetary system, the expectation was they would be like the Solar System, with rocky inner planets like Earth and Mars, and gas giant worlds like Jupiter and Saturn orbiting farther out. The shock has been that most extrasolar systems are utterly unlike ours.

Many extrasolar systems have giant planets, known as 'hot Jupiters', orbiting closer to their stars than the orbit of the Sun's innermost planet, Mercury. If they had been born there, their gas would have been blown away, so they must have formed farther out and 'migrated' inward. Many alien planetary systems have planets many times the mass of our Earth. Such 'super-Earths' are conspicuous by their absence in our Solar System, although there is a claim that such a planet, dubbed Planet Nine, orbits way beyond the outermost planet, Neptune.

In some extrasolar systems there are planets in highly elliptical orbits reminiscent of comets, and in others there are planets that share a single orbit. There are even planets that orbit the wrong way around their stars. Such 'retrograde' planets are hard to explain since planets are believed to congeal out of the left-over debris of star formation. Since the debris swirls around a star in a single direction, any planets should do too, as in our Solar System.

We thought we knew a lot about planet formation from studying our Solar System. But it turns out we have much to learn. The hope is that NASA's new exoplanet hunting telescope TESS and ESA's CHEOPS spacecraft will improve our current understanding.

HOW DO WE DETECT EXOPLANETS?



Planets shine by reflecting the light of their parent stars. But since they are small compared with their stars, they are faint. And, since they orbit close to their stars, it is virtually impossible to detect them directly. Think of a firefly flying in the beam of a search light. So most exoplanets are instead found indirectly, through their influence on their parent stars.

One method exploits the fact that gravity is a mutual force – a star tugs on a planet but a planet also tugs on the star, causing the star to wobble slightly. The effect is hard to see but quite easy to measure in the light of the star. As the star moves towards and away from us, it creates a periodic shift in frequency of its light. This 'Doppler effect' is the light equivalent of a police siren becoming shriller (higher frequency) as it approaches and deeper (lower frequency) as it recedes.

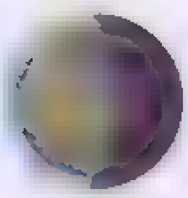
Another method for finding planets is possible if the orbit of a planet regularly takes it across the face of its star as seen from Earth. Such 'transits' dim the light of the star slightly. If the size of the star is known, the dip reveals the size of planet. If its mass is known from the Doppler method, then its density can be deduced. Very few planetary systems are edge-on from our point of view, so observing transits requires monitoring huge numbers of stars.

ABOVE If a planet's orbit regularly takes it across the face of its star, then the star's light will dip slightly, which means that the planet's size can be calculated

Yet another method of finding planets relies on the focusing, or 'gravitational lensing' of the light of a more distant star, by a star and its planet. As the planet orbits its star, the brightness of the background star varies, revealing the presence of the planet.

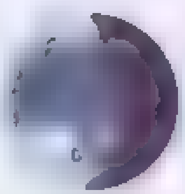
Though these indirect methods have proven successful, astronomers would like to be able to dispense with indirect methods and photograph extrasolar planets directly. In 2004, a group of astronomers reported the first detection of a giant planet candidate by direct imaging.

THE FIVE MOST INTERESTING EXOPLANETS IN THE SEARCH FOR LIFE



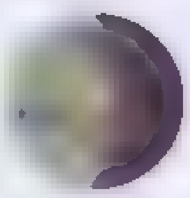
PROXIMA CENTAURI B

This is an Earth-mass planet orbiting the cool red dwarf star, Proxima Centauri, once every 11.2 days. Being the closest exoplanet to Earth, it has the most exciting potential.



TRAPPIST-1 E

This is just over half the mass of Earth and orbits its red dwarf parent every 6.1 days. It is one of seven known planets in the Trappist-1 system, three of which are in the 'habitable zone' (see p92)



KEPLER-62F

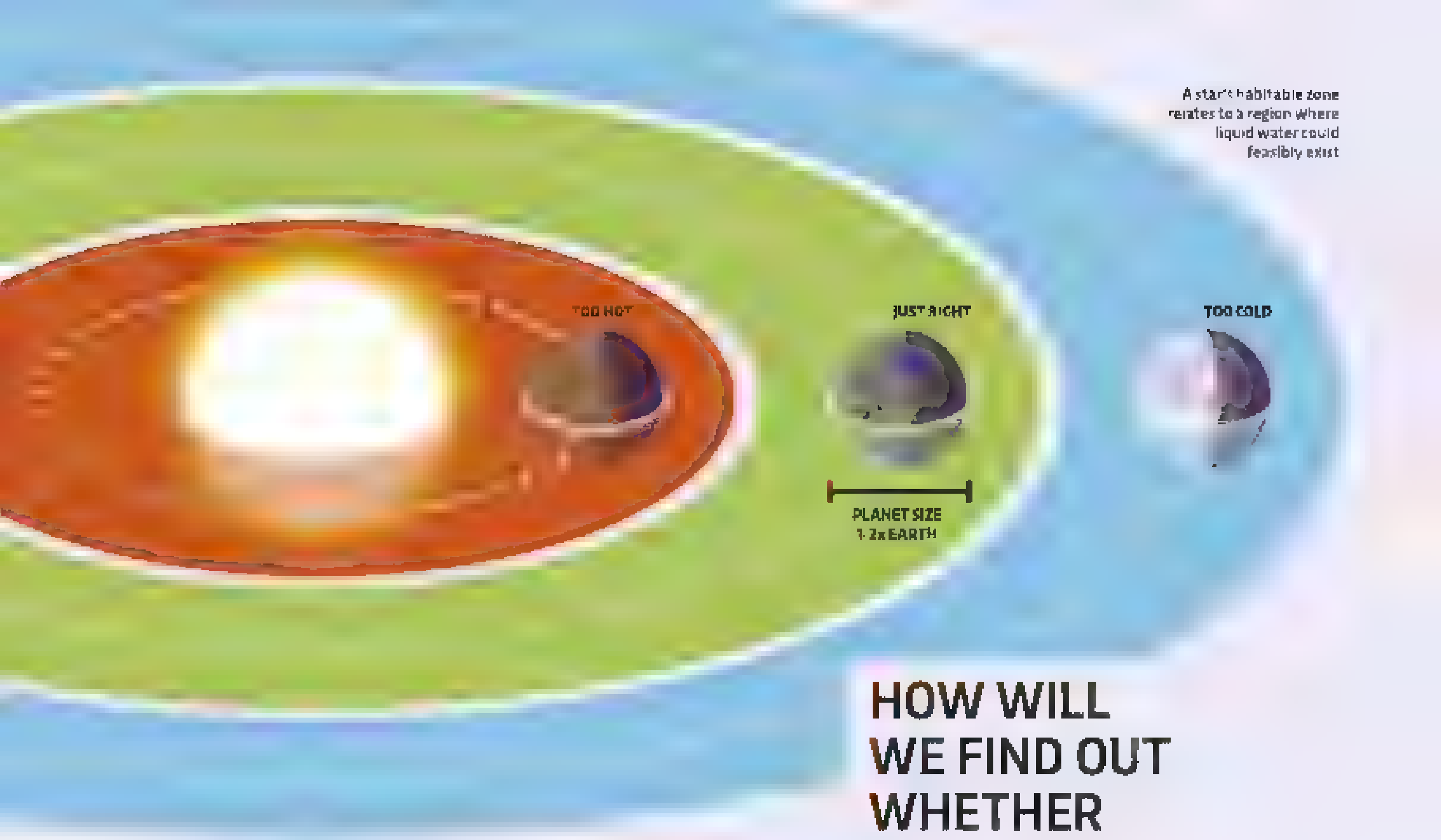
This has a mass about three times bigger than Earth's. It orbits a dwarf star once every 267 days. The star is cooler than the Sun, so for it to be warm enough for oceans, it needs a thick atmosphere

KEPLER-186F

This is about 1.5 times more massive than the Earth. It orbits once every 130 days in the habitable zone of its parent star. It is colder than Earth, but a thick atmosphere might make it cosy for life

KEPLER-452B

This planet is about five times as massive as Earth and 60 per cent bigger. Crucially, it orbits a star that is like the Sun, and is 1,400 light-years from Earth. The orbit takes just over one Earth-year



HOW DO WE KNOW WHAT EXOPLANETS ARE MADE OF?

"Never, by any means shall we be able to study the chemical composition of the stars," said French philosopher Auguste Comte in 1835. He was wrong. When heated, atoms and molecules shine with light at characteristic wavelengths (energies). If they are in the cool atmosphere of a star, then they absorb light at those same wavelengths. This creates a series of black lines like a supermarket barcode in the stellar 'spectrum'. In the same way, when an exoplanet moves in front of its star, so that the starlight passes through the planet's atmosphere on its way to Earth, there is the potential to see the barcode of substances in the planet's atmosphere.

So far, this technique has revealed a number of substances such as sodium, carbon monoxide, carbon dioxide and water in the atmospheres of extrasolar planets. The detection of molecular oxygen, an unstable gas, would indicate its continuous creation by living things.

27,710
Distance in light years of farthest confirmed exoplanets SWEEPS-04 and SWEEPS-11

3,584
Number of known exoplanets

165,000
The number of years it would take a modern spacecraft to reach Alpha Centauri, the closest star system to the Solar System

41.32 trillion
Distance in km to nearest exoplanet Proxima Centauri b

4,300
Temperature in °C of the hottest exoplanet KELT-9b

HOW WILL WE FIND OUT WHETHER EXOPLANETS ARE INHABITED?

Since we have only one example of life – what's found here on Earth – we have no choice but to look for 'life as we know it'. And all life on Earth requires water. This has given rise to the idea of a star's 'habitable zone'. A planet orbiting within this region is close enough to its star that water does not freeze and far enough away that it does not boil. This not-too-cold, not-too-hot 'Goldilocks zone' is quite narrow around the huge majority of stars, which are red dwarfs, but wider around Sun-like stars.

Recently, the concept of the habitable zone has been considerably widened. This is because of the discovery of ice-covered oceans located on Jupiter's moon Europa and Saturn's moon Enceladus. Although they intercept so little light that they should be frozen solid, they are heated by tidal stretching and squeezing from their parent planets. There is also the possibility that a planet orbiting far from its star might be kept warm by radioactive heat from its own rocks if it is swaddled in a blanket of greenhouse gases.

Life, it seems, might survive in environments far removed from those on Earth.

GRAVITATIONAL WAVES

Over 100 years ago, Albert Einstein predicted that space-time could be warped and stretched. It turns out that he was right

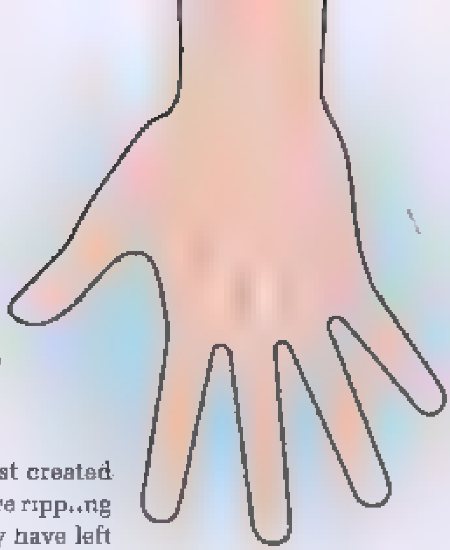
Gravitational waves are ripples in the fabric of space-time. They were predicted to exist by Albert Einstein in 1916, although he then got cold feet and retracted his prediction the following year, only to re-make it in 1936.

Specifically, gravitational waves are a prediction of Einstein's revolutionary theory of gravity, the 'General Theory of Relativity', which he presented in Berlin in November 1915, at the height of World War I.

Whereas Isaac Newton had maintained that there was a 'force' of gravity between the Sun and Earth, like a piece of invisible elastic tethering the Earth to the Sun and keeping it forever in orbit, Einstein showed that this is an illusion. No such force exists. Instead, the Sun creates a 'valley' in the space-time around it, and the Earth travels around the edge of the valley rather like a roulette ball in a roulette wheel.

We cannot see the landscape of space-time because space-time – a seamless amalgam of three space dimensions and one of time – is a four-dimensional thing, and we are mere three-dimensional creatures. That is why it took a genius like Einstein to realise that what we think of as matter moving under the influence of the force of gravity is in fact matter moving through warped space-time. As the American physicist John Wheeler said: "Matter tells space-time how to warp and warped space-time tells matter how to move."

According to General Relativity, space-time is no mere passive backdrop to the events of the Universe. Instead it is a 'thing', which can be bent and stretched and warped by the presence of matter. And, if it can be distorted in this way, argued Einstein, it can also be jiggled. When this happens, an undulation of space-time spreads outwards at the speed of light like concentric ripples on a pond, a gravitational wave.



HOW ARE GRAVITATIONAL WAVES MADE?

Wave your hand in the air. You just created gravitational waves. Already, they are rippling outwards through space-time. They have left the Earth. They have passed the Moon. In fact, they are well on their way to Mars. In about four years' time they will reach the nearest star system. We already know that one of the three stars of Alpha Centauri is circled by a planet. If it hosts a technological civilisation that has built a gravitational wave detector, at the beginning of 2022, it will be able to pick up the gravitational waves you created by waving your hand a moment ago!

Mind you, the detector will have to be super-sensitive. This is because gravitational waves, which are produced whenever mass changes its velocity, or 'accelerates', are extremely weak. The reason for this is that gravity itself is extremely weak (like space-time is extremely stiff). Imagine banging a drum. Now imagine replacing the drum skin with something a billion billion times stiffer than steel. That's the stiffness of space-time. This extreme stiffness means that only the most violent movements, such as the merging of super-dense bodies like neutron stars and black holes, can create appreciable gravitational waves.

44
Number of years between the construction of the first LIGO prototype at the California Institute of Technology in Pasadena and LIGO's first detection of gravitational waves

1.3 billion
The number of years the gravitational waves detected on 14 September 2015 had been travelling across space to Earth

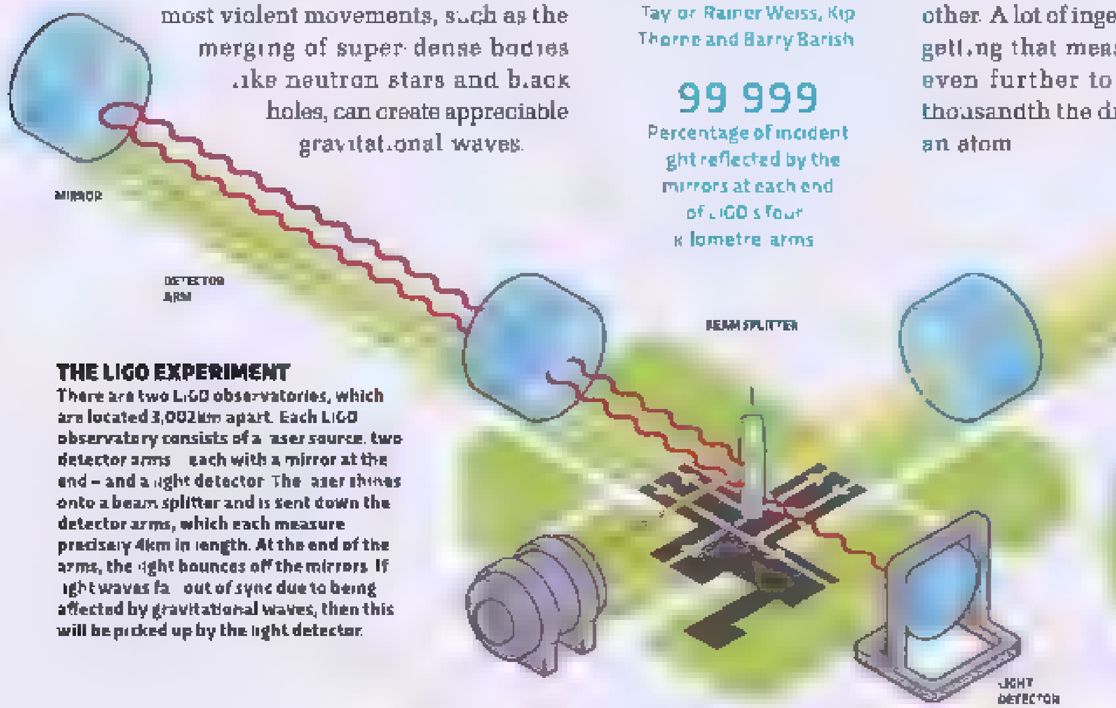
5
Number of gravitational wave researchers so far awarded Nobel Prizes: Russell Hulse, Joseph Taylor, Rainer Weiss, Kip Thorne and Barry Barish

99.999
Percentage of incident light reflected by the mirrors at each end of LIGO's four-kilometre arms

HOW ARE GRAVITATIONAL WAVES DETECTED?

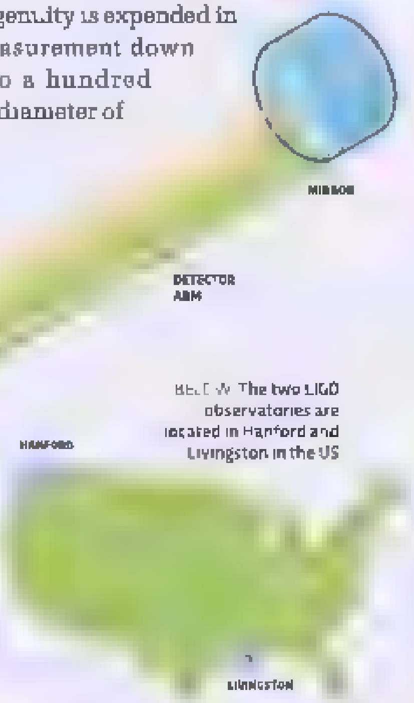
As gravitational waves pass, they stretch space in one direction and squeeze it in a perpendicular direction, then alternate, repeatedly. The effect felt on Earth of the waves from a black hole merger is extremely small, typically a change in the length of a body by a mere billion billionth of its size. So the only way to detect such a small effect is with a big ruler. Enter the Laser Interferometer Gravitational Wave Observatory (LIGO). At Hanford in the state of Washington is a four-kilometre ruler made from laser light. Three thousand kilometres away at Livingston, Louisiana, is an identical ruler. Each site has two tubes, which form an L-shape down which a megawatt of laser light travels in a vacuum more empty than space.

LIGO splits laser light into two and sends it down each arm, where mirrors bounce it back to a point where the light is re-combined. If the crests of the two waves coincide, the light detected is boosted. If the crest of one coincides with the trough of the other, the light is cancelled out. So LIGO is sensitive to changes in the length of one arm relative to the other. A lot of ingenuity is expended in getting that measurement down even further to a hundred thousandth the diameter of an atom.



THE LIGO EXPERIMENT

There are two LIGO observatories, which are located 3,002km apart. Each LIGO observatory consists of a laser source, two detector arms – each with a mirror at the end – and a light detector. The laser shines onto a beam splitter and is sent down the detector arms, which each measure precisely 4km in length. At the end of the arms, the light bounces off the mirrors. If light waves fall out of sync due to being affected by gravitational waves, then this will be picked up by the light detector.



BELOW: The two LIGO observatories are located in Hanford and Livingston in the US

SOURCES OF GRAVITATIONAL WAVES

Neutron stars and black holes are the endpoints of the evolution of massive stars. When they explode as supernovas, paradoxically their cores implode. If the core is below a threshold mass, the stiffness of 'neutrons' – a so-called quantum property – can stop the shrinkage, leaving a star about the size of Mount Everest, but so dense that if you took a lump of its material measuring the same size as a sugar cube, it would weigh as much as the entire human race. If the core is above the threshold mass, no known force can stop the shrinkage and the star collapses to become a black hole.

Since most stars are born in pairs – our Sun being a rare exception – the expectation is that the most massive binaries end their lives as a pair of black holes, a pair of neutron stars, or a black hole orbiting a neutron star. The mere fact that the stars are orbiting each other – and changing their velocity, or accelerating – means that they radiate gravitational waves. This saps the stars of orbital energy, causing them to spiral in towards each other, at first very slowly, but, as time goes by, faster and faster.

Such an event, known as the 'binary pulsar', was observed for the first time in 1974. The source was two black holes that smashed together, coalescing into a single giant black hole and releasing a powerful burst of gravitational waves as space-time buckled and contorted.

Six bursts of gravitational waves have now been detected.

The hope is that gravitational waves will lead us to a long sought-after quantum theory of gravity

BEFORE MERGER

The two black holes were held in orbit around each other by their mutual gravitational pull. Their huge mass caused space-time to warp around them. Energy radiated away in the form of gravitational waves, leading to their orbits drawing closer.

DURING MERGER

The black holes accelerated as they grew closer, reaching speeds close to the speed of light. Eventually they merged into a single deformed black hole that radiated enormous amounts of energy as gravitational waves.

AFTER MERGER

Once the black holes had merged into a single entity, the system settled into equilibrium with a regular spherical shape, and the emission of gravitational waves dropped rapidly. This is known as the 'ringdown'.

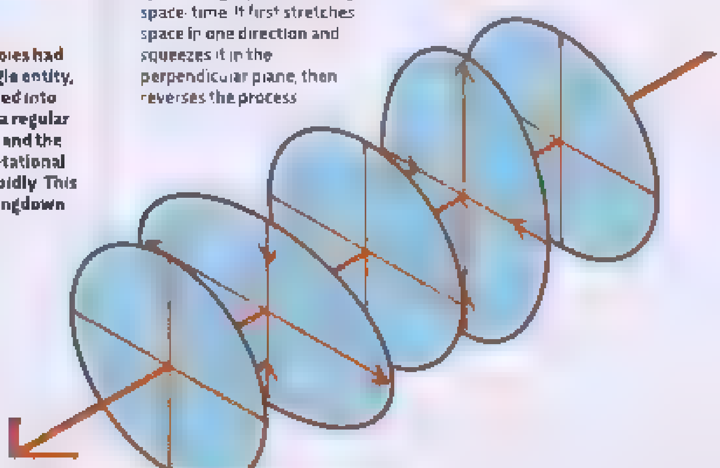
WHAT CAN GRAVITATIONAL WAVES TELL US?

Gravitational waves have the potential to point towards a better, deeper theory of gravity. We know that Einstein's theory breaks down in the infinitely dense 'singularity' found at the heart of a black hole and at the beginning of time in the Big Bang. The hope is that gravitational waves will lead us to a long sought-after quantum theory of gravity.

They also have the potential to reveal the behaviour of super dense matter inside neutron stars. Perhaps, even more excitingly, they could tell us about the birth of the Universe. In the standard picture, the Universe in its first split second of existence went through an incredibly violent expansion known as inflation. This should have left a relic background of gravitational waves, which we may be able to detect and decode.

Gravitational waves truly provide us with a new 'sense'. We have always been able to see the Universe, with our eyes and telescopes. Now, for the first time, we can hear the Universe too. Gravitational waves are the 'voice of space'. So far, we have heard some sounds at the edge of audibility. Nobody knows what the cosmic symphony will sound like, but as we improve the sensitivity of gravitational wave detectors, we hope that we will discover things of which nobody has ever dreamed.

As a wave travelling at the speed of light passes through space-time, it first stretches space in one direction and squeezes it in the perpendicular plane, then reverses the process



BLACK HOLES

These weird, yet fascinating bodies are characterised by gravity so immense that not even light can escape

Black holes are regions of space where gravity is so strong that nothing, including light, can escape. Hence the blackness of a black hole.

The modern picture of black holes is provided by Einstein's General Theory of Relativity. The theory tells us that a mass like the Sun creates a valley in the space-time around it into which other bodies fall. In this picture a black hole is a bottomless well from which light cannot escape without being sapped of every last shred of its energy.

For reasons we do not fully understand, nature appears to have created two main classes of black holes: 'stellar mass' black holes and 'supermassive' black holes, ranging in mass from millions of times the mass of the Sun to a most 50 billion times its mass. There is some evidence of the existence of a class of black holes between stellar mass and supermassive but so far astronomers have found very few of these 'intermediate mass' black holes.

Stellar mass black holes are the endpoint of the evolution of massive stars. However, nobody knows the origin of supermassive black holes, or why there appears to be one in the heart of pretty much every galaxy, including our very own Milky Way. It is a chicken and egg puzzle. Does a galaxy of stars form first, and then later a supermassive black hole in its heart? Or does a supermassive black hole pre-date a galaxy and form the seed about which a galaxy of stars congeals?

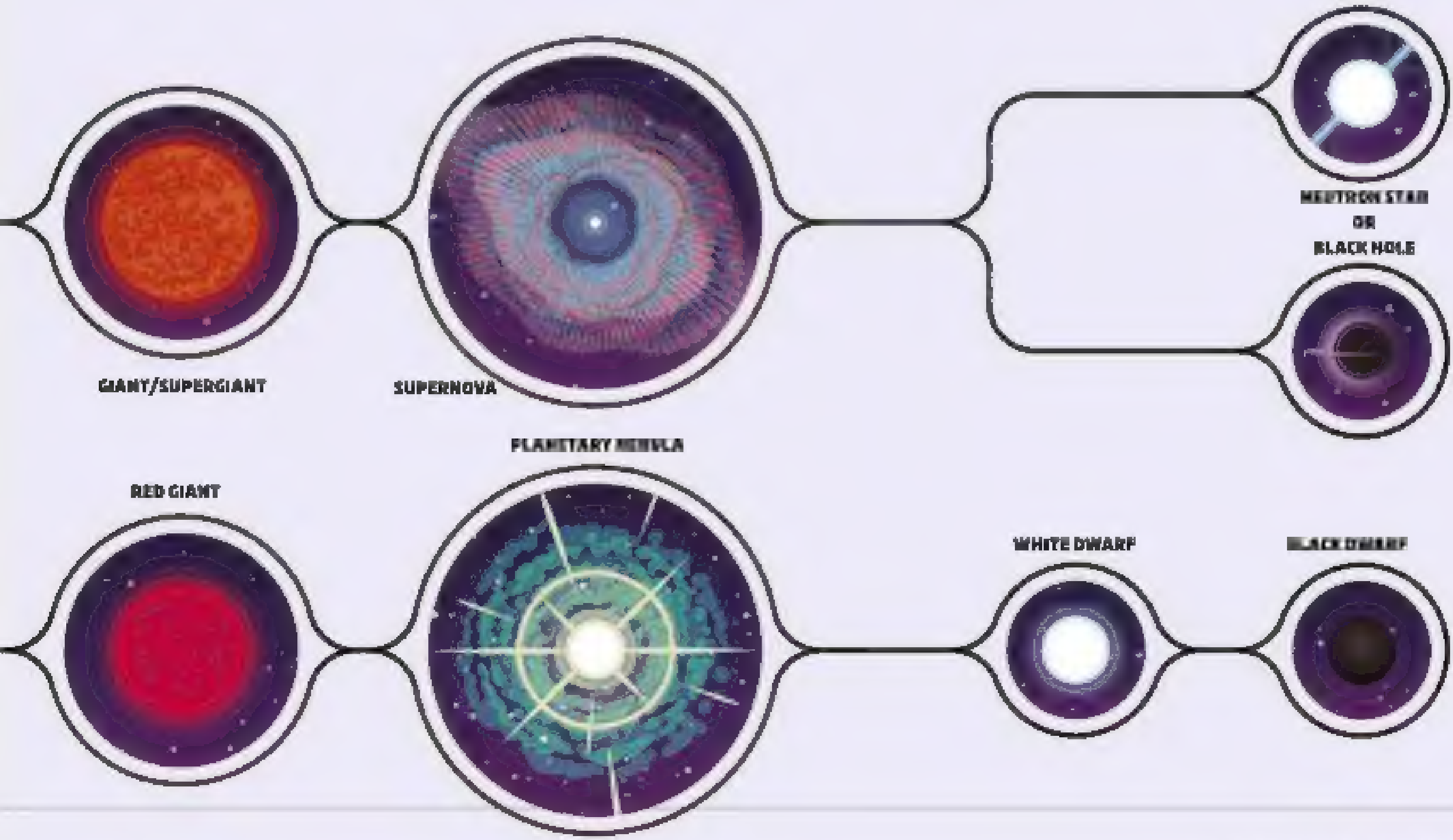
The heating of matter as it swirls down onto a supermassive black hole creates an 'accretion disk' so super-hot that it can pump out 100 times more energy than a galaxy of stars. This is the power source of active galaxies, the most energetic objects in the Universe.

THE LIFE CYCLE OF A STAR

When a cold, dark cloud of interstellar gas and dust shrinks under its own gravity, a star is born. As the gas is squeezed, it gets hotter. When the core temperature exceeds 10,000,000°C, nuclear reactions ignite, and the ball of gas lights up as a star.

A star represents a temporary balance between the forces of gravity trying to shrink a ball of gas and its internal heat pushing outwards. The star fuses the cores, or 'nuclei', of hydrogen, the lightest atom, into the second lightest, helium. The mass difference between the initial and final product appears as the energy of sunlight, according to Einstein's famous formula $E=mc^2$. This conversion has an important effect on a star like the Sun. As helium is heavier than hydrogen, it falls to the centre. The nuclei of atoms repel each other, and the bigger the nucleus, the stronger the repulsion. For two new nuclei to stick together and make a heavier nucleus, they must slam into each other at high speed, which in practice means at high temperature. The core of the Sun will only ever be dense and hot enough to fuse together hydrogen into helium. But this is not the case with more massive stars. Their cores eventually become dense and hot enough to fuse helium into carbon, carbon into oxygen, oxygen into neon, and so on. Such stars end up with an internal structure reminiscent of an onion, with the heaviest elements in the centre surrounded by concentric shells of less and less heavy elements.

The end point of this build-up process is iron. Its creation sucks nuclear energy from the core of the star, shrinking it into a tiny, ultra-dense ball of neutrons – a neutron star. In-falling material converts implosion into explosion – a supernova. But, if the core is massive enough, no known force can stop gravity crushing the core out of existence – in fact, crushing it all the way down to a point of infinite density known as a 'singularity'. Cloaked in the impenetrable wall of an 'event horizon', this is a black hole.



BELOW: Stars are born when a gas cloud collapses and matter accumulates on a protostar. A high-mass star is 10-150 solar masses (one solar mass = the mass of our Sun), a low-mass star is 0.08-10 solar masses. The main sequence takes up 90 per cent of a star's life – the Sun is currently at this stage. High-mass stars have shorter lives, and will become giants or supergiants before exploding into a supernova, where all but 10 per cent of the original mass is ejected. The star's core will then collapse. Depending on the size of the core's mass, it will either become a neutron star or a black hole. Low-mass stars have longer lives. After the main sequence, they will become red giants. Eventually, the outer layers of gas will be ejected and the star's core will contract to form a white dwarf. Theoretically, the star could then cool to form a black dwarf, but the Universe is still too young for this to be proved.

THE ANATOMY OF A BLACK HOLE

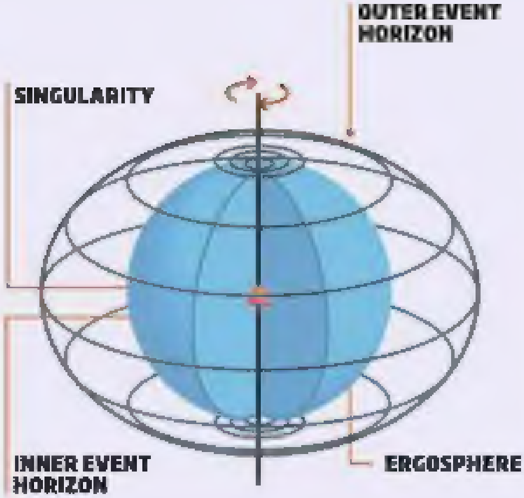
Once a massive star has shrunk to form a black hole, nothing is left (as far as we know) but a bottomless pit of space-time. A black hole is surrounded by an event horizon, an imaginary membrane that marks the point of no return for in-falling matter and light. Inside the event horizon, and at the heart of the black hole, Einstein's General Relativity predicts the existence of a point of infinite density called a 'singularity'. Yet once you reach this, Einstein's theory – and all of physics as we know it – breaks down.

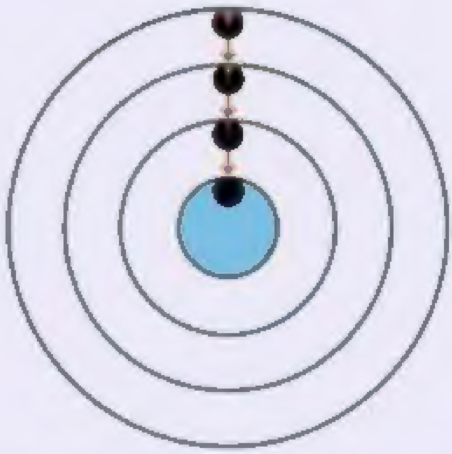
Imagine an astronaut falling feet first into a black hole. When they are at a circumference corresponding to 1.5 times the circumference of the black hole, gravity is so strong it bends light into a circle around the hole, so they can see the back of their head! Near a stellar-mass black hole, the huge difference in gravity between the astronaut's head and feet will tear them apart before they reach the event horizon. However, this tidal effect is negligible near a supermassive black hole, and the astronaut can cross the event horizon with no ill-effect.

Einstein's theory predicts that time flows more slowly in strong gravity. So, if you were to observe the astronaut falling down to the black hole from a safe distance, they would appear to move in ever slower motion, and stop altogether on reaching the event horizon. Although they would fall through into the hole, never to appear again, their image would be frozen on the event horizon, gradually fading as light from the image struggled to climb out.

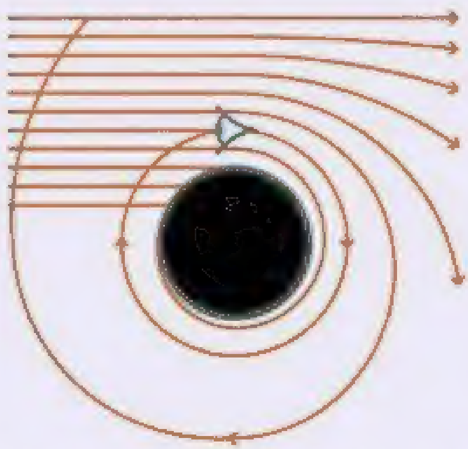
In the case of a rotating, or 'Kerr', black hole, there is a twist. In effect, these have two horizons. When the astronaut crosses the outer one, and enters the 'ergosphere', they are dragged around by a tornado of space-time. They can still gain energy from the hole's rotation and be ejected from the black hole. But once they cross the inner event horizon, there is no going back.

Nobody knows what the inside of a black hole looks like. But the unfortunate astronaut can no more avoid being crushed to death than you can avoid tomorrow.





ABOVE As a light source nears the event horizon, fewer and fewer photons are able to escape (shown in orange) from the black hole's gravitational clutches. Once the event horizon is reached no photons are able to escape



ABOVE The gravity of a black hole is so immense that it bends light into a circle round the hole. This means that someone falling in would be able to see the back of their own head

6
Diameter in kilometres of the black hole that would form if the matter of the Sun could be squeezed hard enough.

4.3 million
Mass in multiples of the Sun's mass of Sagittarius A*, the giant black hole at the heart of our Milky Way.

1.8
Diameter in centimetres of the black hole that would form if the matter of the Earth could be squeezed hard enough.

40 billion
Mass in Suns of the biggest known black hole in the Universe: S5 0014+81.

1
Diameter in metres of the Jupiter-mass black holes left over from the Big Bang which some have suggested could make up the Universe's invisible dark matter.

Marcus Chown is an award-winning cosmology writer and broadcaster. His next book *The Ascent Of Gravity* is out in April

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